CONTROL STRATEGIES TO CONSERVE ENERGY IN ALL-AIR HEATING VENTILATION AND AIR CONDITIONING SYSTEMS

William James Morrison

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Control Strategies to Conserve Energy in All-Air Heating Ventilation and Air Conditioning Systems

Report directed by Assistant Professor Clift M. Epps

Commercial and residential buildings consume approximately thirty-seven percent of the energy used in the United States. Heating ventilation and air conditioning (HVAC) for these buildings requires one-half to two-thirds of this energy. Energy required for HVAC systems can be reduced by improving the HVAC control systems in existing buildings. Six typical all-air HVAC systems are considered in this report. The various control methods that are being applied to these systems are discussed. Results of work in this area by others is summarized. This report contains an extensive bibliography. Control system improvement saves energy in most applications with little or no loss of comfort.

CONTROL STRATEGIES TO CONSERVE ENERGY IN ALL-AIR HEATING VENTILATION AND AIR CONDITIONING SYSTEMS

by

William James Morrison

B.S., University of Missouri, 1969

A report submitted to the Faculty of the Graduate School of the University of Colorado in partial fulfillment of the requirements for the degree of

Master of Science

Department of Civil and Environmental Engineering

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This Report for the Master of Science Degree by

William James Morrison

has been approved for the

Department of

Civil and Environmental Engineering

by

Morrison, William James (M. S., Civil Engineering)
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Heating Ventilation and Air Conditioning Systems
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This abstract is approved as to form and content.

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CHAPTER I

INTRODUCTION

Energy crisis is an overworked phrase, but a concise description of the personal, national and international dilemma confronting all people. As a nation, we are faced with declining petroleum supplies and increasing demand. This predicament is the cause of an intense search for alternative energy sources and more efficient energy consuming processes.

Residential and commercial uses of energy in the United States accounted for 28.16 quadrillion BTUs of the 75.95 quadrillion BTUs[37] consumed in 1977. This represented approximately thirty-seven percent of the national consumption that year, a percentage that has been fairly constant since 1973. Residential and commercial consumption of energy in existing structures is a significant burden upon the nation and property owner. Fortunately, there exists a tremendous potential for energy savings in these structures.

Superscript numbers refer to references at the end of the report.

New structures are being designed and built with energy conservation in mind. This is the result of the economics of our time and the response to various federal, state, or local regulations in the area of energy budgets for new buildings. For this reason, energy savings in new buildings will not be considered in this review.

Energy Saving Possibilities in Existing Buildings

Energy savings in existing buildings will be the focal point of this report. Many possibilities exist for conservation of energy in existing buildings. The building envelope may be improved to minimize transmission of energy by adding insulation. Solar gains for air-conditioned buildings can be reduced by architectural treatments such as shading, solar film on windows, and use of light exterior colors. Infiltration losses can be reduced by caulking, sealing and weather stripping where needed. The lighting and power requirements can be significantly improved by reducing nonproductive illumination, using more efficient luminaires, the use of light color surface treatments on the interior to maximize light utilization, and installing proper sized motors with high power factors. Often, the energy efficiency of a structure can be increased by improving the existing routine HVAC maintenance programs[3] and by tuning up the HVAC system with a good testing and balancing program.[29]

A fertile area for energy conservation is the controls and their application to the HVAC system. Control strategy can be as complex as automating the entire control system or as simple as lowering the set point of a thermostat.

A brief review of the process leading to implementation of control system modifications follows.

Energy Conservation Programs

Organization of the Program

An effective energy conservation program must rest upon a methodical analysis of the problem. John S. Blossom[4] has developed an eight step problem solving approach to aid in development and implementation of energy conservation programs.

1. Define the objective. An energy conservation program objective should be established and defined. The objective will generally be to save money, but it may be to save energy or reduce usage of a specific fuel. These are not necessarily coincident objectives. It is possible to save money spent on energy by using a cheaper energy source. Conversely, energy can be saved by using a more energy efficient, but more expensive process. In any case, the objective should be put in writing to insure that it remains consistent as the program develops.

2. Define the problem. The problem is the source of the objective. Typical problems include increasing costs, reduced availability of energy, or new government regulations on energy usage.

3. Establish a data base. This is information of a factual nature that relates to the problem being considered. The owner's requirements and constraints such as budget limits or comfort levels are included in the data base. Also, physical and technical parameters of the problem such as size and operation of the HVAC equipment, measured energy consumption rates, indoor temperatures, outdoor temperatures and other measured data necessary to establish the actual operating conditions of the building are gathered. Historical energy consumption records and the operation schedule of the building should be included in the data base. Development of the technical information for the data base could require considerable effort, depending on the building under study. The U. S. Air Force reports an average of 132 man-hours of data gathering and engineering time for each building studied in a comprehensive energy audit of 2000 large buildings.[9] Once the data base has been established, the next step is to pause and make sure the study is on the right track.

4. Review with the owner. This is the time to insure the objectives, problem definitions and criteria are in consonance with the owner's goals. Approval of the

program by the owner should be required prior to proceeding with the next step.

5. Develop alternative solutions. The alternatives should include the cost of making no changes and the feasibility of ceasing to use the building entirely. Within these extremes, several technical solutions to the problem should be formulated. The initial cost and operating expenses for each solution should be estimated at this point in the program. The next step is to select the technical solutions that are best suited for the case being studied.

6. Recommend a specific program. Alternative solutions should be compared and a specific recommendation prepared for the owner. If the recommendation is accepted, the next step is to implement the program.

7. Implement the program. This phase includes design and construction, if necessary, of the physical changes to be made under the approved program.

8. Follow up. Systematic monitoring of results is vital to assess the success of the program. Following up should include comparison of the objective with the results and a determination if the original problem was solved.

Categories of Conservation Efforts

Technical energy conservation efforts can be grouped into categories on the basis of cost effectiveness, energy saved, investment required, ease of implementation, management effort required or others. A classification

system of some sort is necessary to bring order to the alternative solution selection process. Clift M. Epps[6] proposes grouping alternatives into four general categories based upon cost effectiveness and ranked by initial cost. Cost will most likely be the common denominator for any other basis of classification. The following categories will be used to organize the control strategies reviewed in this report.

Low-cost Adjustments. Easily implemented measures such as effective maintenance; shut down of HVAC equipment when spaces are unoccupied; reducing excessive lighting levels in noncritical task areas; adjusting thermostat set points; and reducing the amount of ventilation air to the allowable minimum. These actions require no capital investment and are accomplished by adjustment of maintenance and operation procedures. Any costs would be labor and management expenses usually resulting in paybacks of one year or less.

Quick Fix Modifications. Easily accomplished measures such as installing time clocks to start and stop equipment; arranging control sequencing such that heating and cooling do not occur simultaneously; installing process temperature reset controls; and installing thermostats with wider throttling ranges. Process temperature reset attempts to match the supply air temperature more closely to the space requirements. If the space is near the desired

temperature, the supply air temperature is reset closer to the space temperature. Excessive heating or cooling is minimized. Thermostat throttling ranges are the spread of temperatures over which the thermostat output ranges from full pressure (in the case of pneumatic systems) to minimum pressure. A tight throttling range might be 3^{o}F and a wide throttling range might be 10^{o}F to 20^{o}F. Photocells or time clocks to control lighting might be effectively employed in low use or high daylight concentration areas or on night security circuits. These modifications would generally be easily accomplished, require minor investment of capital funds, and usually have simple paybacks of three years or less. Simple payback being defined as the amount of time it takes for cumulative annual savings of fuel and operating expenses to equal initial investment. Effects of the tax structure, fuel price escalation, and the cost of money are not considered in simple payback computations.

Minor System Retrofit. Projects such as adding economizer cycles which use outside air for cooling; conversion to centralized control of the building's systems; and installation of more sophisticated sensing elements, controllers, and controlled devices would fall into this category. Also, additional lighting controls such as more extensive standard switching or low voltage switching might also be employed. Calculated payback periods on these modifications could be greater than three

years and should be based upon accepted economic evaluation procedures.

Major System Conversion. This phase would include conversion of fan or pumping systems from constant volume to variable volume operation, altering duct systems, adding devices to reclaim waste energy, utilizing alternate energy sources such as solar energy, making physical improvements to the building's envelope, and integrating lighting and switch modifications based upon tasks performed, space function, space utilization and time. These activities would require considerable capital and manpower investments and may yield simple paybacks of greater than ten years.

The average owner has probably already progressed through step one of the above program and many owners are well into steps two and three in their conservation programs. As the easy savings ideas are implemented the next steps generally require more exhaustive economic and technical study. These areas will be briefly considered in this report.

Economics of Retrofit Programs

Renovating structures or HVAC systems to conserve energy can result in significant expenditures of capital funds. These investments must be analyzed to determine the best use of funds devoted to energy programs. A first review of the project should be made by simple payback

calculations. The prime drawback with simple payback is the failure to account for the time value of money, energy price escalation and the effect of the tax structure upon the results of a project. Therefore, simple payback calculations are best used in order of merit comparisons between various alternatives or for short periods of time. A simple payback analysis is quite sufficient for before-tax paybacks of three years or less.[17] Within this period of time, fluctuations in the cost of money and the price of energy will not have a severe impact upon the validity of simple payback results.

If the simple payback calculations show paybacks greater than three years, then payback calculations should be made taking into consideration the cost of money, taxes and future energy rate escalations. Paybacks on this basis can be used with some degree of confidence up to ten years or so.

All payback calculations are at best educated estimates. Conditions, formulas and procedures have been developed for these estimates that range from the simple procedures described above to very sophisticated methods. If order of merit considerations drive the analysis, the simplest method possible should be used to determine payback. If the financial soundness of the investment is to be determined, more rigorous methods might be in order.

Considerations in a Retrofit Decision

The technical and economic factors that lead to a retrofit decision must accommodate other constraints on the retrofit design. The impact of building codes, comfort levels, additional control complexity and utility usage patterns must be checked for each retrofit project.

Most structures will be covered by local, state or national building codes that set minimum standards for the functions of the HVAC system. For example, the outside air ventilation minimum is usually specified on an occupancy or floor area basis. National organizations such as ASHRAE publish standards[2] to guide building officials in preparation of their codes.

The comfort level in a building is a very subjective parameter. HVAC modifications must be made with the goal of maintaining the occupied spaces within a clearly recognized comfort zone. A tremendous amount of work has gone into development of widely acceptable comfort zones. Here again, ASHRAE has a standard[2] that defines conditions at which most people will be comfortable. Optimum use should be made of widely recognized and accepted comfort standards when determining internal design conditions. Gains attributable to lowered comfort should not be credited to a retrofit of the HVAC system. A loss of productivity of even one percent in a commercial activity due to lowering the comfort level may negate any financial gains

for that reduction in energy conservation. Retrofit proposals that have the potential to adversely affect the comfort level must be evaluated with that in mind.

Retrofit ideas that significantly increase the control complexity may not be feasible or desirable. Locations geographically remote from the technical support necessary to keep the system operational are poor candidates for complex control schemes. Installation and maintenance problems involved with these systems will cancel any advantages that may accrue from the control system. Recent advances in control element reliability have greatly increased the practical applications of new control schemes and must not be discounted. Still, control systems must be as simple as possible to accomplish the required action regardless of the availability of technical expertise.

Retrofit proposals that do not save energy, but rather redistribute its usage to take advantage of utility company rate structures may become very poor investments indeed. Utility rate structures can be changed to reflect changing demand patterns, thus eliminating the economic rational for the retrofit in question. The primary devices in this category are demand controllers. A demand controller generally monitors and attempts to limit maximum metered electric demand.[7] Utility rate structures that surcharge customers based upon peak demand are the impetus behind demand controllers. A demand controller is usually

preset to a maximum allowable electric demand. It monitors electrical usage by various means. As the electrical usage of the building approaches the preset limit, the controller begins to shut off electric devices in the building in a preselected sequence. The electric devices shut down first are generally those with some energy storage capacity such as water heaters or the HVAC systems. Loads are kept off for predetermined periods of time if necessary before other loads are shed and the original device returned to line. In this manner, the peak electrical demand of the structure can be spread out over a longer period of time at a lower value. The net effect is to hold down the demand surcharge and thereby reduce the electric bill. Energy may or may not be saved.

Currently the utilities' industry generally remains neutral on the use of demand controllers.[7] This might be expected since the rate structure can be periodically adjusted to develop the revenue necessary for operation and expansion of their facilities. If load limiting devices begin to affect revenues, the utility rate will of necessity be adjusted to bring in the required revenue.

Effect of Retrofit Activities on Normal Operations of the Facility

Many retrofit decisions are made without proper evaluation of the disruption that may occur during construction or installation of the modification. Often the

consequences of a retrofit decision upon normal operation of the facility only become apparent when the contractor begins work. These consequences should be as carefully weighed as other considerations in the planning stages of an energy conservation modernization. Two otherwise equal alternatives in terms of cost, payback, energy savings and time for completion might be quite different in effect on the facility during installation. This is the primary area that sets envelope modifications apart from control strategies in an energy conservation program. Envelope modifications will most likely involve reglazing, hanging new doors or adding insulation to wall systems. These activities will create some interference with the use of the building. Control system modifications may be accomplished in a large part in mechanical rooms with little interference in occupied spaces. Minimizing the time spent in occupied spaces by construction activities will be a tremendous advantage to the facilities engineer and will avoid productivity declines of the employees. This advantage to control systems modifications must be considered in the energy conservation program analysis.

Scope of This Report

The remaining material in this report will center upon the modifications of control systems to conserve energy in commercial and residential applications. The

control strategy of a HVAC system is the easiest part of the process to change. Often the physical modifications necessary to implement new control strategies are the easiest and least disruptive choices of several alternative plans to save energy.

CHAPTER II

ALL-AIR CONSTANT VOLUME SINGLE ZONE

The Basic System

A typical all-air constant volume single zone system is shown in Fig. 1. For the purposes of this report, the system schematics omit safety devices such as firestats and service lines such as control air supply and electrical feeders. In general, the schematics will only depict portions of the HVAC system germain to the control strategies discussed.

The sequence of operation of this system will be analyzed in detail in order to establish basic terminology. The analysis will begin with the fans off, outside air colder than inside air and inside air colder than the thermostat set point. The fan-damper motor interlock will cause the outside and exhaust dampers to be closed when the fans are off. The chilled water valve will be closed and the hot water valve will be open. Starting the fans signals the damper motor to position the dampers to allow a predetermined amount of outside air, return air, and exhaust air. The amounts remained fixed unless the dampers

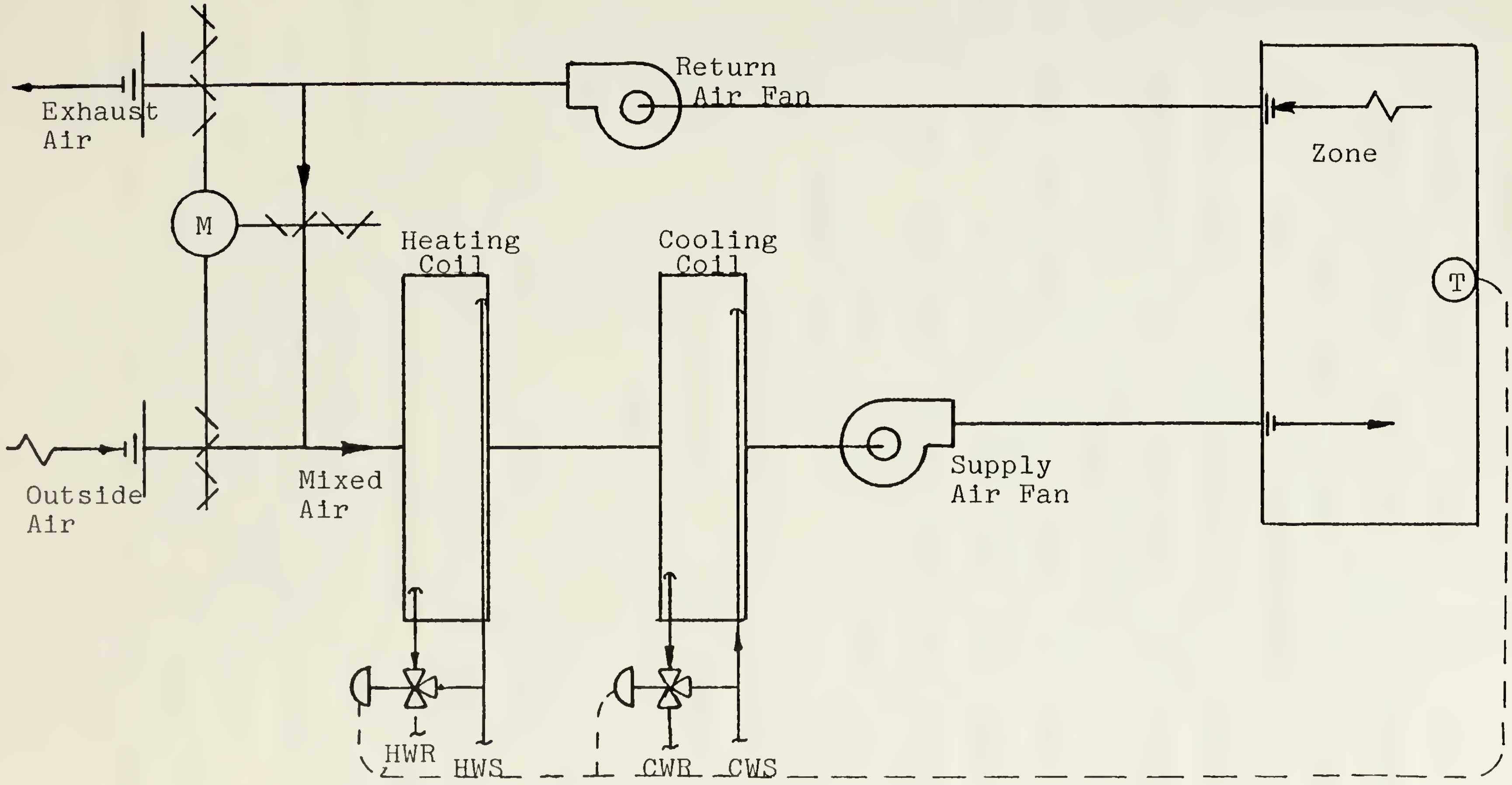

FIGURE 1. BASIC CONSTANT VOLUME SINGLE ZONE SCHEMATIC

are manually adjusted or the fans shut off. The air circulated by the fans is heated by the hot water coil and begins to warm the space. When the space temperature falls within the throttling range of the thermostat, the space is under control. See Fig. 2 for the definition of set point and throttling range. The thermostat will attempt to maintain a temperature of 74°F in the zone. This temperature is the set point of the thermostat and is at the midpoint of the throttling range. In this case, the throttling range is from 72°F to 76°F. Over this four degree temperature span, the thermostat output ranges from minimum pressure to maximum pressure. This figure also depicts the relationship between the controller and the controlled devices in response to the value of the controlled variable. Or in this case, the relationship of the pneumatic thermostat output and the water supply valve position in response to the space temperature. This control logic diagram is idealized in that linear operation of the devices is shown and the dynamic response of the system is neglected. Continuing with the sequence of operation, the logic diagram shows that at the set point of the thermostat, both valves will be closed. An increase in space temperature will cause the chilled water valve to open. This will cool the circulating air and attempt to bring space temperature back to the setpoint. The system remains

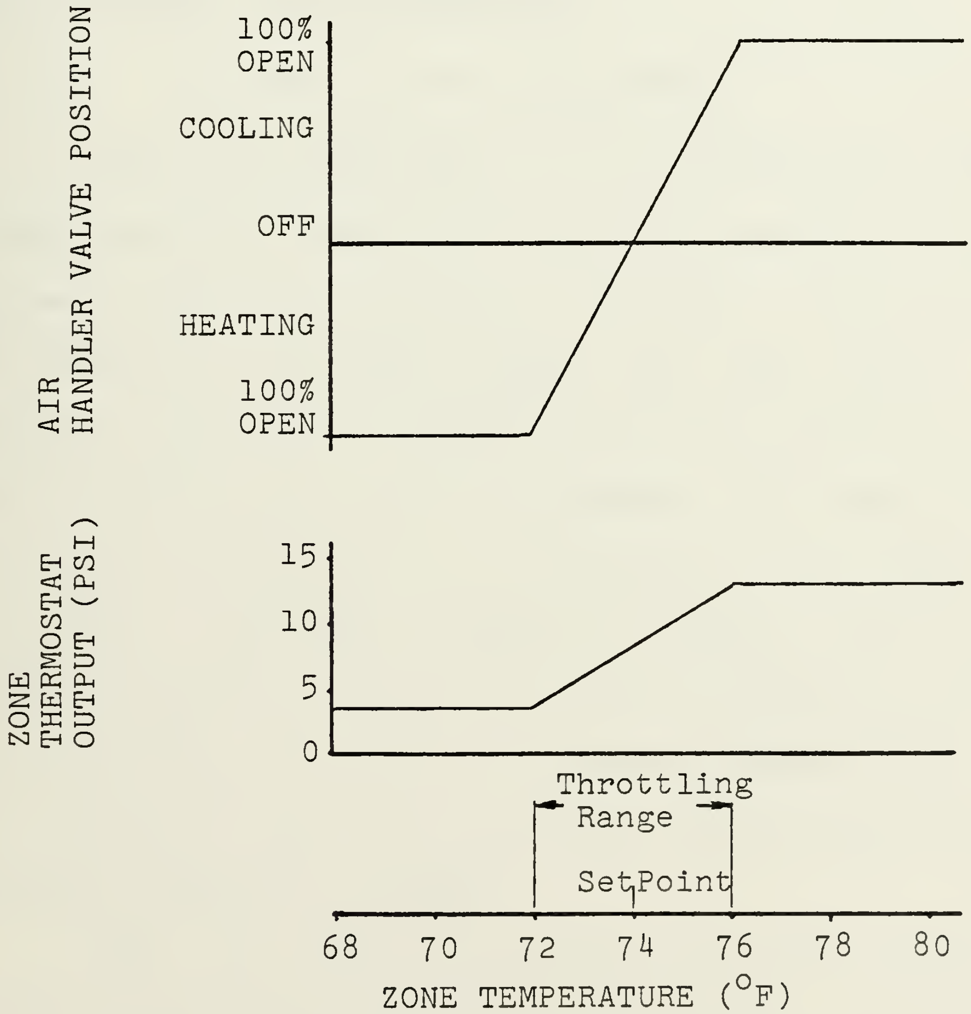

FIGURE 2. CONTROL LOGIC FOR SINGLE ZONE CONSTANT VOLUME SYSTEM

under control if space temperature is within the throttling range.

This control strategy, although simple, has several drawbacks. Primary among these are year-round fan operation, fixed amount of outside air and maintaining nearly constant space temperature.

Low Cost Control Adjustments

The first adjustment to be considered for the system described above should be manual shutdown of the equipment when the building is unoccupied. This will save fan energy and the thermal energy that would normally be expended conditioning ventilation air and maintaining the space thermostat set point temperature. The space temperature would be permitted to float while the building is unoccupied. In extreme climates or seasons, the system could be manually switched to a night thermostat rather than completely shut down. The night thermostat would be set to maintain the minimum allowable space condition and close the outside air damper.

Next, the outside air damper should be adjusted to provide the minimum allowed or acceptable ventilation rate. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) publishes a standard that suggests minimum ventilation rates for most building applications.[2] It is interesting to note

that these minimums are generally based upon requirements to control or dilute odors generated by occupancy, living habits or other sources.[1] The amount of ventilation air required to provide necessary oxygen to occupants and to prevent objectional concentrations of carbon dioxide is generally much less than the minimum set by ASHRAE.[1] The energy cost of excess ventilation is directly proportional to the mass of the outside air entering the space and the inside-outside air enthalpy difference.[21] Therefore, the absolute minimum ventilation rate consistent with health and comfort should be provided.

Another low cost energy savings adjustment is the thermostat set point. Adjusting the thermostat set point to a lower temperature for heating loads and higher temperature for cooling loads will save a significant percentage of the annual energy used by both residential and commercial buildings. Two single family dwellings studied during the winter of 1973-1974 showed fuel savings of twenty percent as a result of lowering the thermostat set point $4^{o}F$ from $72^{o}F$ to $68^{o}F$.[38] Similarly, a commercial building studied by computer simulation in the summer of 1974 saved thirty-one percent of the normal annual cooling energy as a result of raising the thermostat set point $3^{o}F$ from $75^{o}F$ to $78^{o}F$.[14] This saving was verified in part by actual metered energy consumption.[8] Published studies are in accord that energy savings result from thermostat set

point. The magnitude of the savings depends upon the type and location of the building.

Quick Fix Control Modifications

These modifications of the all-air single zone system could be extensive. Automatic thermostat setback for night time and periods of time when the building is unoccupied is a primary quick fix modification. A two set point thermostat with a twenty-four hour timer would typically be applied in a residence. The day set point (74°F) would drive the thermostat output until a preselected time (9:00 p.m.). The timer would then switch to the night set point (60°F) which would drive the thermostat output until the cycle was completed by returning to the day set point at a preselected time (5:00 a.m.). This would be a 14°F setback for eight hours on a daily basis. A commercial application of the same principle would likely utilize a seven-day clock to permit weekend and holiday setbacks. In addition, a commercial or otherwise unoccupied building setback strategy would provide for the fan system to cycle from the night set point rather than operate continuously, close outside air dampers, shut down unnecessary exhaust fans and deactivate mechanical cooling.

Studies dealing with night thermostat setback in residences have been widely published.[8,38,25] They are unanimous in claiming approximately ten percent energy

savings with an 8-10°F setback for approximately eight hours at night. Residences that are able to accommodate two eight-hour setbacks per day have been predicted (using a well regarded computer simulation) to save approximately twenty percent of the annual heating energy that would normally be used in a dwelling maintained at a constant temperature.[19] Savings in most commercial applications of setback strategy will be similar or greater due to the potential for longer setback periods and reduced fan energy requirements.

Setback strategy success is sensitive to variation in building type, annual degree days, type of heating source apparatus and the period of the setback. All proposals must be evaluated with the specific characteristics of the installation in mind. Concerning the period of setback, setbacks of four hours or less have not proven to be worthwhile.[38] In fact, buildings with a high thermal capacity and substantial furnace oversize may use more energy on an annual basis under a short setback period than no setback.[39] The reasons for this relate basically to inefficiencies arising in the furnace system during prolonged warm-up of thermally massive structures. If for operational or other reasons short periods of time are available for setback, then setback strategy should not be employed. Most buildings, however, can reduce energy consumption with the proper combination of furnace

size, setback amount and setback period.[13]

Quick fix modification of the single zone constant volume system might certainly include exchanging existing controllers for controllers with a larger throttling range containing a null or dead band. The control logic for this modification is shown in Fig. 3. The thermostat throttling range is 70° to 78°F. The band from 72° to 76°F permits neither cooling nor heating of the circulated air. The zone temperature floats in this range or dead band until it changes sufficiently to open a controlled valve. If the throttling range does not exceed the limits of the comfort zone, significant change of habitability will not occur. The economizer cycle shown in Fig. 3 is described in the next section under minor control system retrofit.

Energy savings for this modification occur for two reasons. Permitting the zone temperature to float with no thermal energy added throughout the dead band is efficient, since this allows the HVAC system to take advantage of the thermal flywheel effect. Closely related to this savings is the benefit of advantageous set points provided by a wide throttling range. This allows the HVAC system to work against smaller indoor-outdoor temperature differences. This strategy has been successfully tested on other HVAC systems, the results of which will be discussed later.

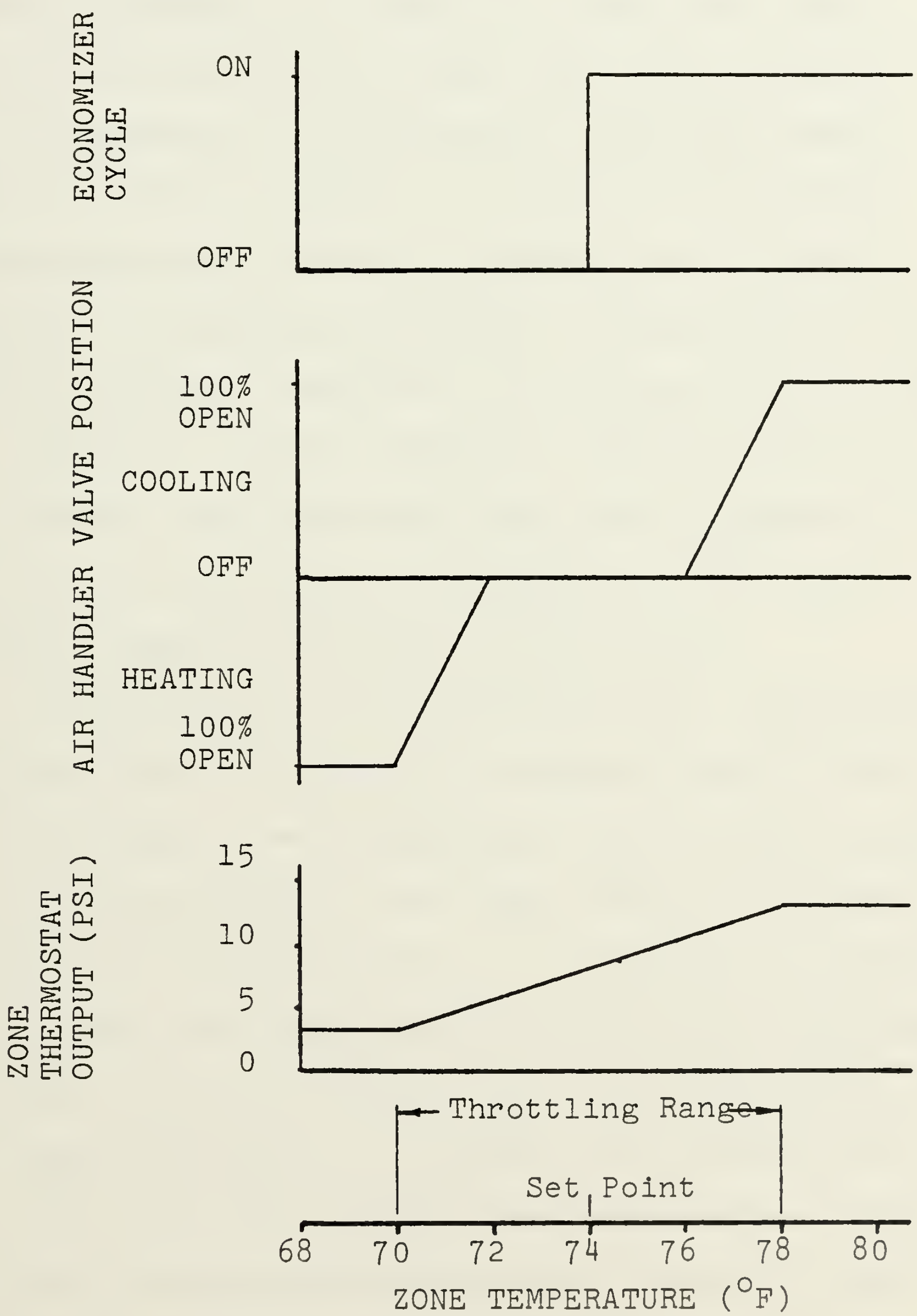

FIGURE 3. MODIFIED CONTROL LOGIC FOR SINGLE ZONE CONSTANT VOLUME SYSTEM

Reset of the heating coil hot water supply temperature is a common control optimization technique. The object of reset is to adjust the hot water supply temperature to match the heating load in the building. A typical arrangement for conventional hot water supply temperature control employs an aquastat at the boiler. This aquastat acts to maintain constant boiler water temperature. Modifying this control system entails the addition of another thermostat that adjusts the set point of the aquastat. The new thermostat might typically be placed outside. The reset rate for this arrangement could vary the water temperature from 180°F to 100°F for an outside air temperature range of 0°F to 50°F.

Energy savings from hot water reset in an all-air single zone system lie mostly in reduced thermal losses due to handling a lower temperature fluid. These savings may not be significant in this HVAC system, but become important in all-water systems. A side benefit of reset is to increase the controllability of the coil discharge temperature. At part heating loads, full temperature supply water alternatively overheats the discharge air which closes the water supply valve resulting in a lowering of the discharge temperature which causes the cycle to repeat itself. Supply water temperatures that more closely match the load do not cause these temperature swings in the discharge air.

Minor Control System Retrofit

Economizer cycles are well established energy savers if properly applied and controlled. The following discussion on the operation of an economizer cycle is applicable to the remaining all-air HVAC systems to be discussed.

An economizer cycle simply uses outside air for cooling before activating mechanical refrigeration. The control logic must use outside air only when it is cool enough and then only if the space thermostat is calling for cooling. Additional control devices required for this retrofit are an outside air thermostat, a mixed air thermostat and a proportional damper motor. The schematic in Fig. 4 depicts these additions for a single zone system.

The system shown has one damper motor mechanically linked to three dampers. Individual motors electrically linked are also common. The linkage dictates that all dampers operate in concert. The exhaust and outside air intake will always be in identical positions to keep the building pressure stable. The return air damper will always be in an inverse position relative to the others. For example, when exhaust is 100% open, return will be 100% closed or when exhaust is 20% open, then return will be 80% open.

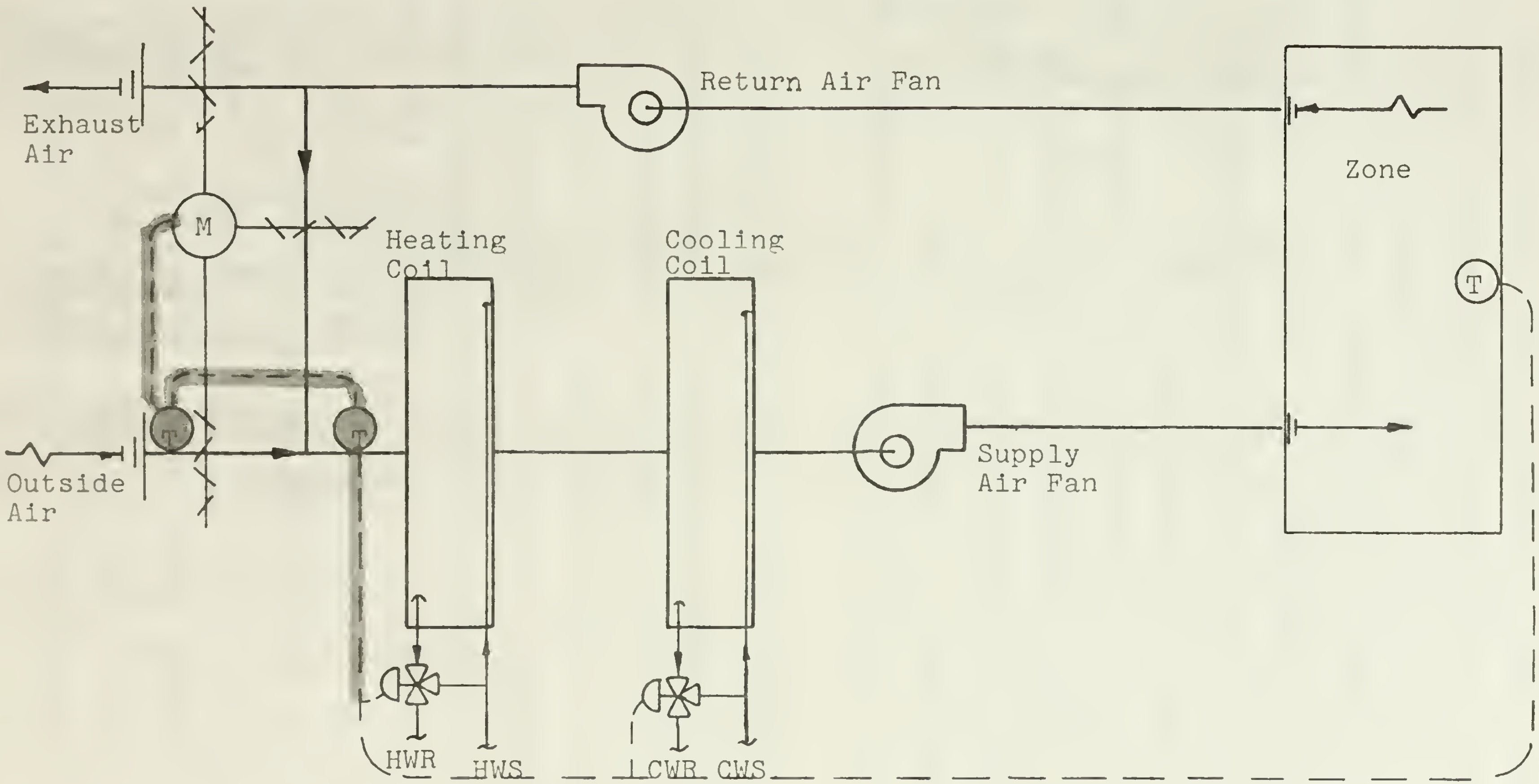

FIGURE 4. MODIFIED CONSTANT VOLUME SINGLE ZONE SCHEMATIC

The economizer status relative to zone temperature and chilled water supply valve position is shown in Fig. 3. In this economizer example, the outside air dampers will be at the minimum position consistent with ventilation requirements at zone temperatures less than $74^{\circ}F$. Zone temperatures above $74^{\circ}F$ will activate the economizer control loop. Zone temperatures above $76^{\circ}F$ will apply mechanical cooling in addition to the economizer. The minimum mixed air temperature allowed for this example will be $55^{\circ}F$. This temperature is generally defined by space comfort criteria and is interrelated with diffuser characteristics, diffuser location and room air motion.

The sequence of operation of the economizer begins with activation of the economizer control loop by the space thermostat. The economizer controls will attempt to operate on the basis shown in Fig. 5, which was adapted from an analysis of economizer operation.[26] Outside air temperatures below the low temperature cutoff and above the high temperature cutoff will position the dampers to provide minimum ventilation air. High temperature cutoff is determined by the design and will generally be the highest temperature air that can still effectively cool the space. Outside air below the low temperature cutoff is too cold to be mixed with return air and still satisfy the mixed air thermostat. In the example shown,

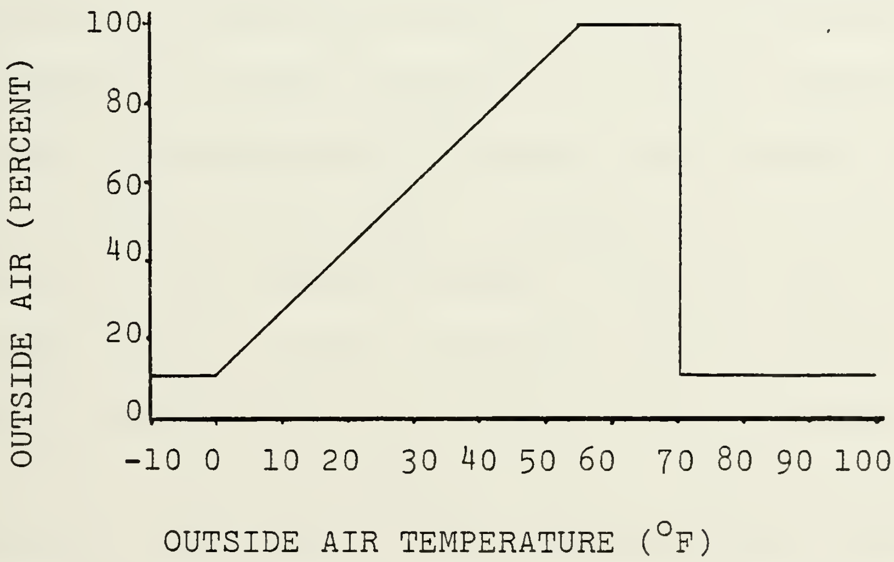

FIGURE 5. DRY BULB ECONOMIZER CONTROL LOGIC

outside air from $0^{\circ}F$ to $55^{\circ}F$ will be proportioned with return air to satisfy the mixed air thermostat's requirement of $55^{\circ}F$. Mixed air temperatures from $55^{\circ}F$ to $70^{\circ}F$ will position the dampers to provide 100% outside air.

Economizer control systems based upon dry bulb temperature can operate inefficiently at some climatic conditions. In reality, the air conditioning load imposed upon a building is a function of both dry bulb temperature and moisture content of the air processed. The enthalpy of a moist air mass is a better indicator than dry bulb temperature of the air conditioning load imposed by the air processed. Enthalpy can be defined as the sum of the internal energy of a mass of air and the product of its volume multiplied by the pressure. Enthalpy takes the moisture content of the air into account. If the system shown in Fig. 4 was operating at a return air condition of $78^{\circ}F$ and 50% relative humidity, the enthalpy of this would be 30 BTUs per pound of dry air.[2] At the same time, the dry bulb economizer could be providing one hundred percent outside air at a temperature of $69^{\circ}F$ to the air handling equipment. If this $69^{\circ}F$ outside air had a relative humidity of 90%, the enthalpy of this air would be 32 BTUs per pound of dry air.[2] Use of outside air would impose an energy penalty of 2 BTUs per pound of dry air upon the mechanical refrigeration.

A simple solution for this problem is to add an enthalpy override to the dry bulb temperature control loop. Enthalpy sensors are placed in the return air and outside air paths. The signals from the sensors are compared. When return air enthalpy is greater than outside air enthalpy, dry bulb control will operate the dampers. When return air enthalpy is less than outside air enthalpy, the override will position the dampers to provide minimum ventilation.

Computer simulations of an economizer installed in a commercial building were made for twenty-five different cities. Dry bulb control produced annual savings in mechanical refrigeration operation time of eleven to fifty-seven percent.[20] Further savings of four to six percent of the total seasonal cooling load have been predicted for installation of enthalpy override on a dry bulb temperature economizer control system.[26] The building, building HVAC system and geographical location all play important roles in the successful application of economizers. The fundamentals should be checked for each proposed retrofit of an economizer.

An intelligent time clock (ITC) is considered a good candidate for minor system retrofit. Basic time clocks start and stop HVAC equipment at predetermined times. The general application is for night setback. The basic time clock turns the thermostat to the day set point in time

to bring the zone under control for occupancy for the predicted worst case weather conditions. As a result, the HVAC equipment runs more hours than necessary during the year. The same thing occurs when the basic time clock turns the thermostat to the night set point. An ITC, which is based upon microprocessor technology, can optimize this process.

Building pickup characteristics are related to the thermal mass capacity of the building and relative size of the furnace. A thermally massive structure with a furnace sized for steady state operation will have a long pickup period or period required to bring the structure to indoor design conditions. Conversely, a thermally light structure with an oversized furnace will require a short pickup period. The pickup characteristics of a building remain constant, can be determined empirically, and then modeled mathematically. For morning pickup, an ITC compares the zone temperature with the building's pickup characteristics in its memory. This comparison allows the ITC to determine the latest time it can turn the thermostat to the day set point and still have the space under control in time for occupancy. Fig. 6 shows hypothetical building pickup characteristics as a function of time and space temperature. At the earliest change-over time the ITC begins to sample the zone temperature and compare it with the building characteristics. If the zone temperature

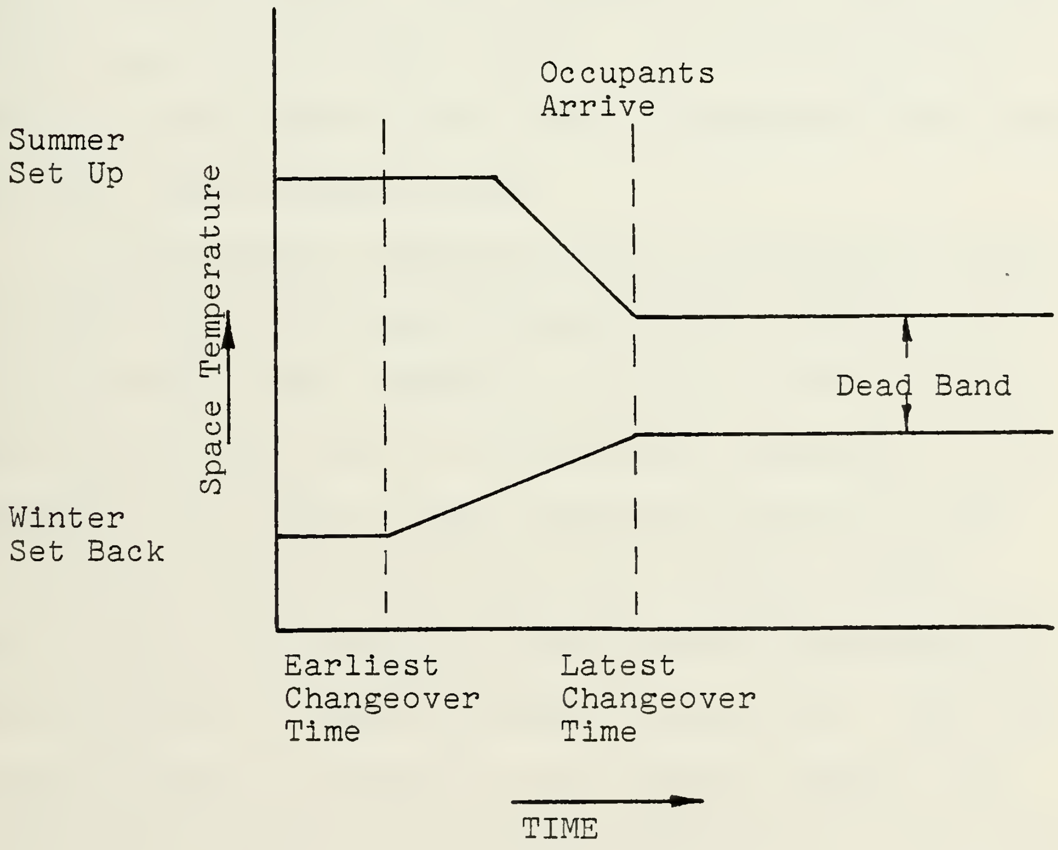

FIGURE 6. Intelligent Time Clock Morning
Pickup Algorithm

falls within the area bounded by the characteristic lines in Fig. 6, then no action is taken. Sampling continues until space temperature is found to be lower or higher than the characteristic lines at the time sampled. At this time the ITC will change the zone thermostat to the day set point. If the building pickup characteristics are accurately modeled, the building will be under control at the time the occupants arrive. If zone temperature is within the dead band at the latest changeover time, changeover will occur automatically.

For evening changeover, the ITC compares outside air temperature with the building's drift characteristics in its memory. This comparison allows the ITC to determine the earliest time it can turn the thermostat to the night set point and not have building conditions drift out of the comfort zone before the occupants depart. Fig. 7 shows hypothetical building drift characteristics as a function of time and outside temperature. The sampling procedure is similar to the morning example described above except that outside temperatures found within the drift envelope will cause the changeover to night set point. Changeover will occur automatically at the latest changeover time.

A recent comparison of an ITC and conventional seven-day cycle time clocks predicted life cycle savings of more than $8,000 in a fifteen year analysis. This was

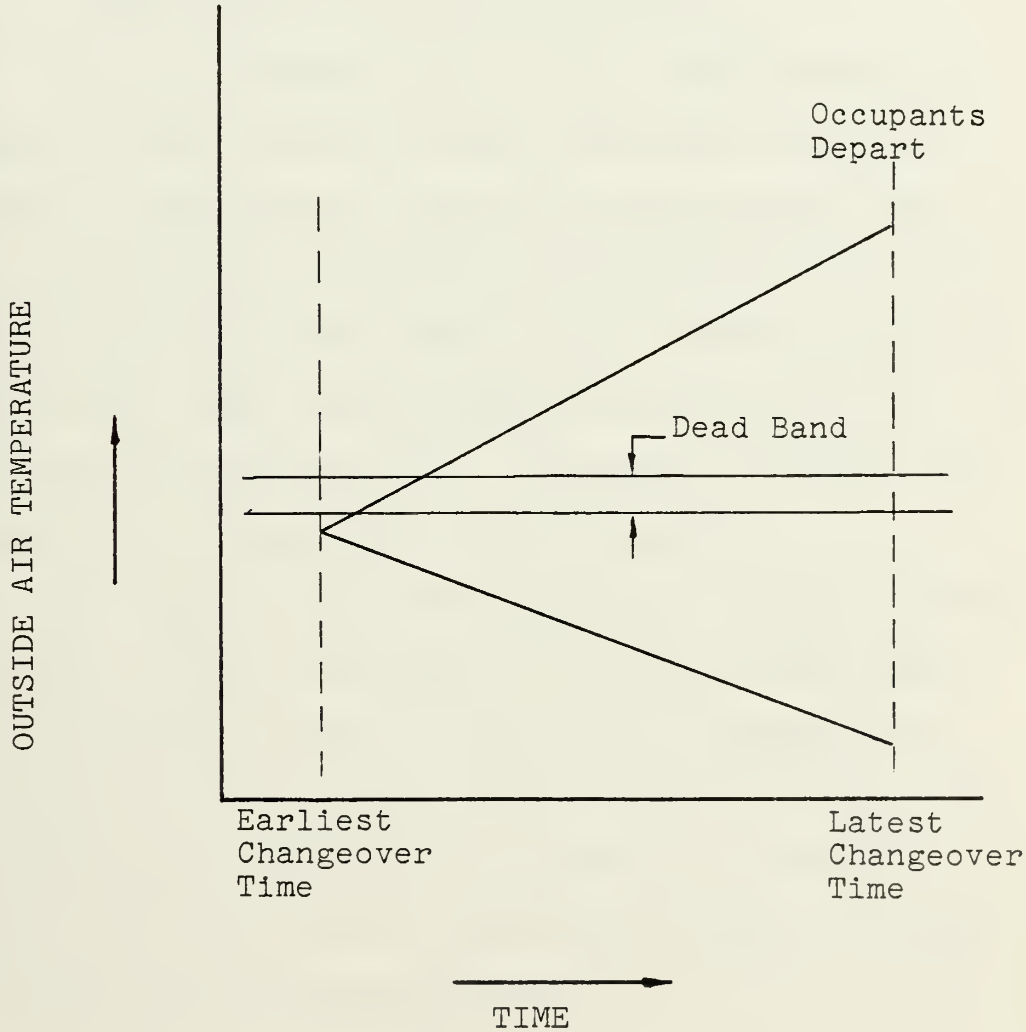

FIGURE 7. Intelligent Time Clock Evening Shutdown Algorithm

for a specific set of economics at a specific building.[34] Proposed installations must be considered on a case-by-case basis.

Major Control System Conversion

All-air constant volume single zone systems are inherently simple and as a result reasonably efficient. The low-cost adjustments, quick fix modifications and minor retrofits discussed above would generally be more than sufficient for this HVAC system. Barring unusual installations, major system conversions could not be easily justified economically. Therefore, no major conversions will be considered for this system.

The single zone system has been a faithful vehicle to consider control strategies to conserve energy that will be employed in most of the all-air systems to be considered in the following chapters of this report. In the systems to follow, basic optimization techniques described here will not be redeveloped, rather reference made to the single zone description.

CHAPTER III

ALL-AIR CONSTANT VOLUME TERMINAL REHEAT

The Basic System

The constant volume terminal reheat system shown schematically in Fig. 8 was widely used prior to the current energy conscious design climate. A constant air volume variable air temperature system, it offered the designer flexibility to serve several individual zones of both heating and cooling loads from a single duct supply system. Flexibility notwithstanding, the reheat system provides excellent control of the conditioned spaces under the most diverse loading conditions. Unfortunately, the energy cost of this type of system is one of the highest when compared to other typical HVAC systems.

The reheat system has a central air handler arrangement similar to the constant volume single zone system. In the reheat system, however, the air handler discharge temperature is controlled by a discharge thermostat rather than the zone thermostat. The set

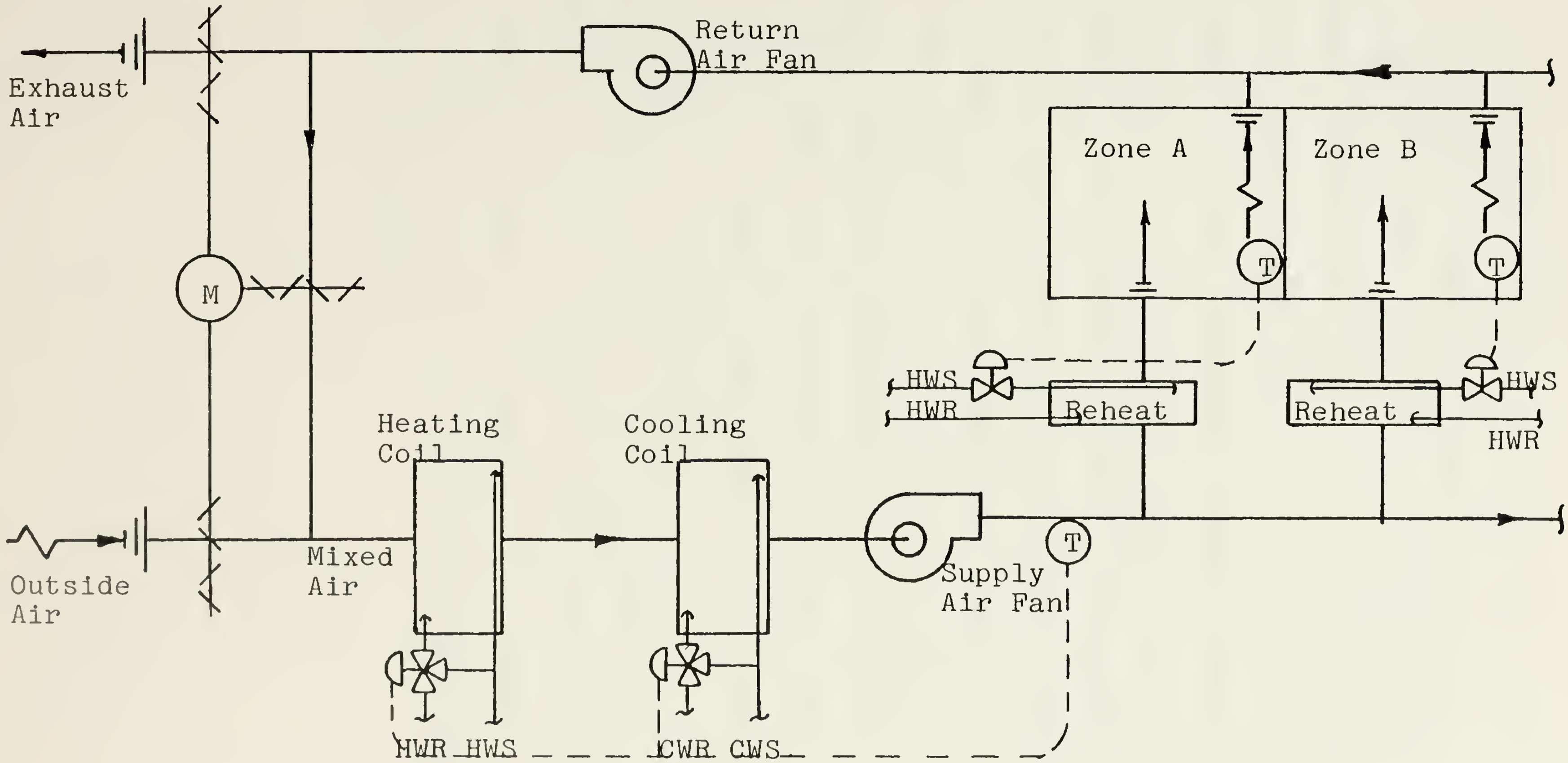

FIGURE 8. BASIC CONSTANT VOLUME REHEAT SCHEMATIC

point of this thermostat is fixed based upon the requirements of the zone having the largest cooling load. A typical value is 55^{o}F. This supply air goes to all zones regardless of individual zone load. If certain zones in the system require warmer air, a zone heating coil controlled by the zone thermostat reheats the air to meet zone requirements. Therein lies the name reheat and the energy waste of this system. Energy is expended to cool air at the air handling unit which is often reheated to a higher temperature at the individual zones.

The control actions of the space thermostat and air handler discharge thermostat are illustrated in Fig. 9. As shown, the air handler discharge temperature control system attempts to maintain the 55^{o}F set point. A value that is fixed regardless of outside or inside conditions. Simultaneously, the zone thermostat operates the reheat coil valve to maintain the zone set point of 74^{o}F. Clearly, several opportunities for energy conservation through control modifications present themselves with this system.

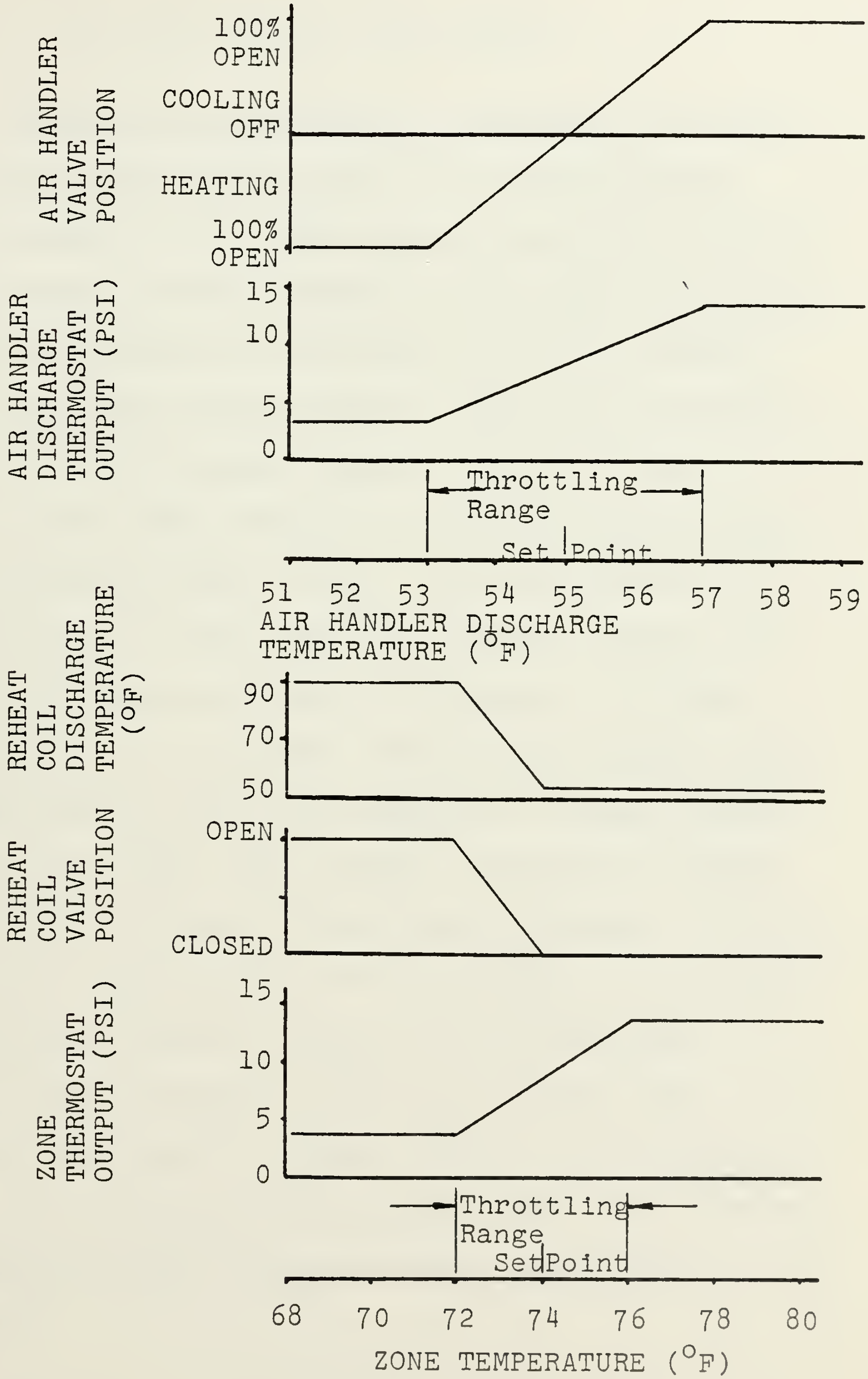

FIGURE 9. CONTROL LOGIC FOR CONSTANT VOLUME REHEAT SYSTEM

Low Cost Control Adjustments

Energy saving adjustments discussed for single zone systems are equally useful for reheat systems. Manual shutdown of the HVAC equipment when the building is unoccupied; minimum outside air settings; and adjusting the zone thermostat set point as low as possible are all excellent energy savers. One minor difference in the case of the reheat system is that the zone thermostat set points should be as low as possible all year to minimize reheat energy. The one exception to this would be for zones that will require cooling year round and seldom need reheat. Set points for these zones should be at the upper limit of the comfort range. These adjustments will save energy for a reheat system as they do in single zone systems. Results of energy savings from unoccupied shutdown are available. Calculations on a hypothetical office building in Columbus, Ohio, predicted annual heating and cooling energy savings of approximately forty-five percent from unoccupied shutdown.[28] Actual results of a shutdown program for a building in Rochester, New York, verified the predicted energy savings of this conservation measure.[15]

Quick Fix Control Modifications

Automatic thermostat setback is effective in reheat system applications as it was in single zone systems. Reset of the hot water supply temperature as discussed in Section 2.3 above will also save energy in a reheat system. Dead band controls and air handler discharge temperature reset schemes are also productive and will be discussed further. Fig. 10 shows additions to the control system (shaded areas) necessary to implement these modifications.

Fig. 11 demonstrates an important change from the basic reheat control logic shown in Fig. 9. The entire HVAC system is now responsive to the zone thermostat. The reheat coil supply valve is controlled by the zone thermostat as before, but also the mixed air thermostat and air handler discharge thermostat have their set points reset by the zone thermostat. The highest allowed reset temperature of the air handler discharge thermostat would be determined by the zone with the maximum cooling load. The objective being to use the warmest supply air capable of handling the worst cooling load. Ideally, zone A in Fig. 10 would be the zone with the maximum cooling load since it is the zone thermostat resetting the discharge thermostat. In most cases, the zone requiring maximum cooling changes during the day as a result of

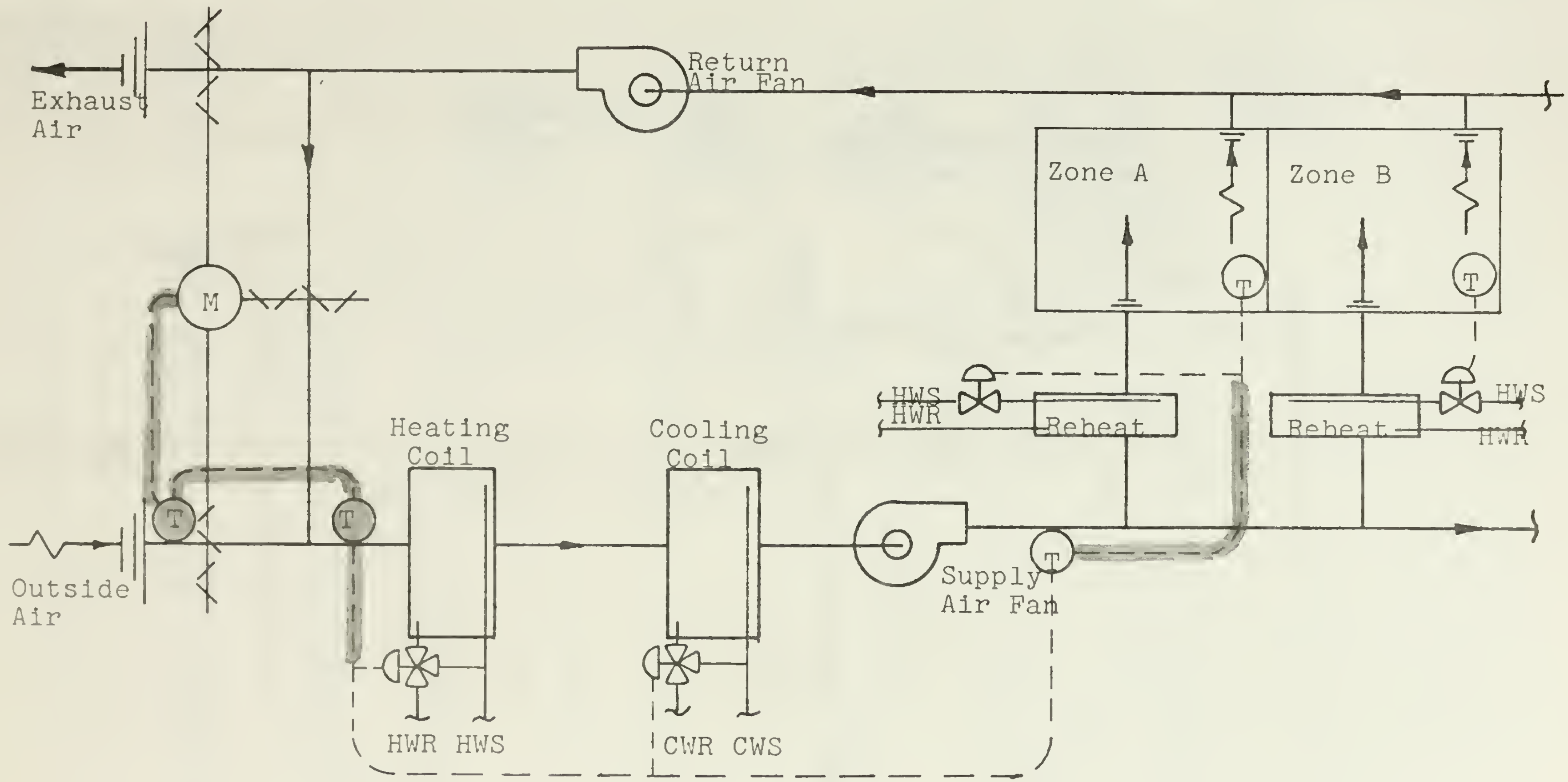

FIGURE 10. MODIFIED CONSTANT VOLUME REHEAT SCHEMATIC

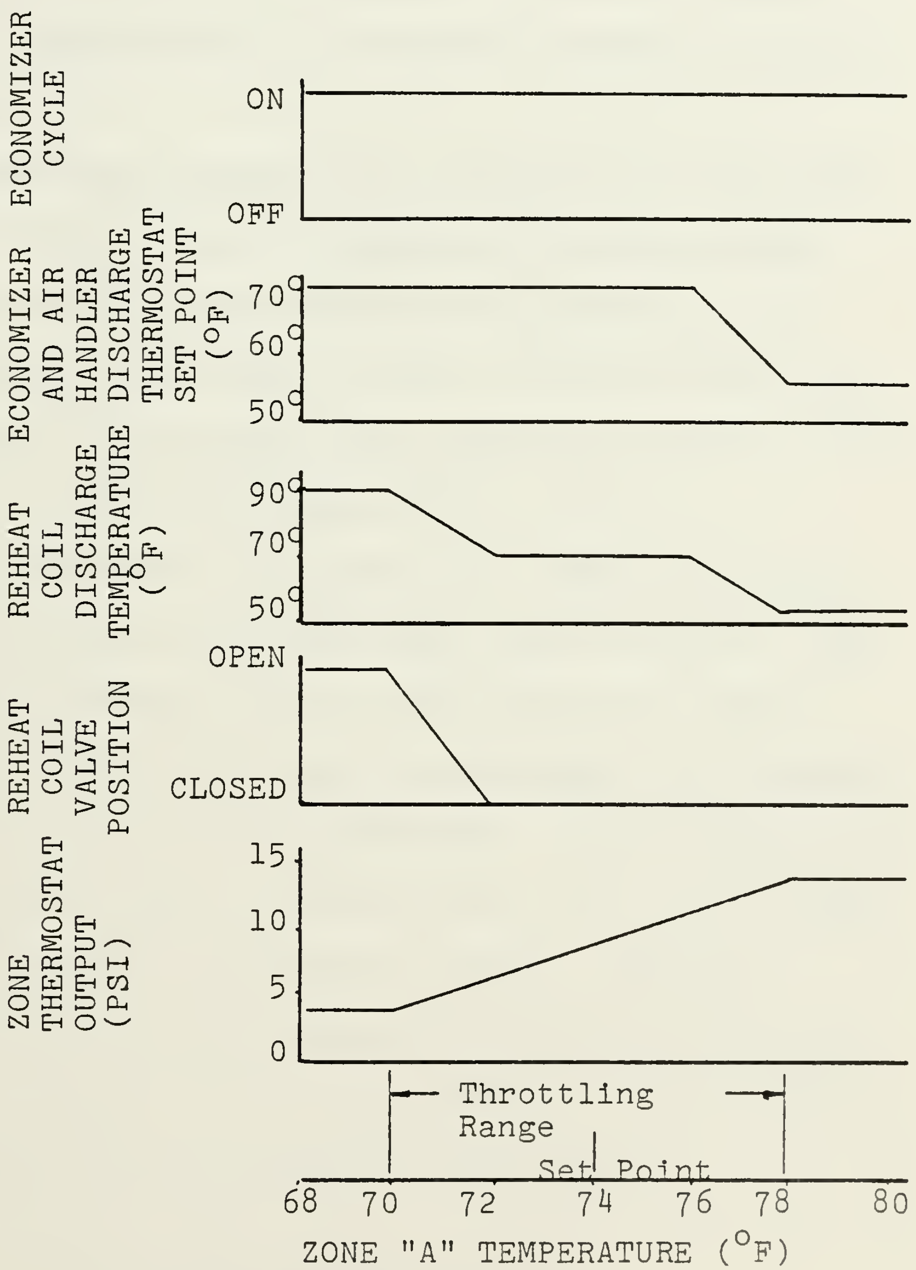

FIGURE 11. MODIFIED CONTROL LOGIC FOR CONSTANT VOLUME REHEAT SYSTEM

solar or occupancy variations. The solution for variable loads is to connect the affected zone's thermostat outputs to a selector which will transmit the highest signal to reset the mixed air and air handler discharge thermostat set points.

The energy savings from resetting the discharge air temperature as high as possible come from reheat savings at all of the zones requiring heating. The energy required for reheat at each of these other zones is much less if the supply air temperature can be raised from 70°F to 90°F rather than 55°F to 90°F.

In addition to discharge air temperature reset, Fig. 11 illustrates the dead band control theory. Zone temperatures between 72°F and 76°F cause the reheat coil valves to be closed and the discharge air thermostat set point to be at the maximum value. Zone temperatures are allowed to float in the dead band until they change enough to activate a controlled device. Predicted energy savings for discharge air temperature reset and dead band controls will be discussed in the next section in conjunction with economizer applications.

Minor Control System Retrofit

An economizer cycle, similar to the system described in Section 2.4 of this report will save energy in a reheat system. The fundamental operation would be

the same as described for the single zone system. Enthalpy override of the dry bulb control would also be an additional energy saver.

Savings as a result of dead band controls, discharge air reset and economizer cycles applied to reheat systems have been reported by a number of authors. A Milwaukee building study isolated the savings from resetting the discharge temperature $6^{\circ}F$ from $55^{\circ}F$ to $61^{\circ}F$.[12] This single modification showed a predicted simple payback of six months. A study conducted for the University of California at San Diego predicted annual heating and cooling energy savings of 79 to 90 percent for control modifications essentially identical to the systems shown in Figs. 10 and 11.[31] Simulations of buildings in Pensacola, Florida, Great Lakes, Illinois, and San Diego, California, also predict excellent energy savings for these modifications.[22]

Another control retrofit worthy of discussion is chilled water reset. As in hot water reset, energy savings accrue from reduced thermal losses in the piping system and there is also the potential for improving the chiller equipment efficiency. Increased controllability is a side benefit of this modification.

Chilled water reset has advantages and disadvantages not encountered with hot water reset. Generally speaking, for centrifugal chillers, lowering the chilled

water supply temperature increases the efficiency of the chiller. On the other hand, lowering the chilled water temperature may impair the cooling coil's ability to handle the latent portion of the air conditioning load. Outdoor dry bulb temperature or as one author proposes, outdoor wet bulb temperature can be used to reset the chilled water supply temperature.[10] The theory being that the latent load on the coil is a function of the outdoor humidity. This would probably be valid for buildings having low latent loads from occupants, their activities, or other sources. Indoor humidity in buildings with significant internal latent loads is not as much a function of exterior conditions and could become a problem. In this case, zone humidity levels may need to be monitored. A humidistat override of the chilled water reset should be provided in case loss of humidity control does occur. Also, in order to insure no zone calling for cooling overheats, override of the chilled water reset temperature by the air handler discharge thermostat should be provided. Obviously, more factors must be considered for chilled water reset than other types of reset. Characteristics of the chiller, latent loads in the building and control system complexity are factors that must be considered when automating chilled water supply temperature reset.

Another method of resetting the chilled water temperature is by checking the water flow through the coil at maximum load conditions. If the control valve is bypassing any water at maximum load, then the water temperature can be manually raised until the valve just opens completely. This will be the warmest chilled water that can be used to satisfy full load conditions. A method of automating this reset technique for all loads conditions and a system of coils has been presented in the literature.[32] This method of reset does not overcome the potential problems of chilled water reset.

Installation of an intelligent time clock as discussed for a single zone system in Section 2.4 of this report is equally applicable to a reheat system. This minor system retrofit will show similar economics for both systems.

Major Control System Conversion

A prime candidate here is conversion from constant air volume to variable air volume. Initial investment and installation problems for this conversion would be greater than for the modifications discussed previously, but economic payback might be very favorable. Analysis of a 100,000 square foot structure in New Jersey predicted energy savings in the range of thirty to forty percent from converting a constant volume reheat system

to variable volume reheat.[27] Variable volume reheat systems will be covered in Chapter VI.

CHAPTER IV

ALL-AIR CONSTANT VOLUME MIXING SYSTEMS

The Basic Systems

Dual duct and multizone are two types of mixing systems commonly encountered. They have the capability to handle both heating and cooling loads simultaneously while offering good controllability of space temperatures. Mixing systems produce parallel paths of air, one hot and one cold, that are blended to produce supply air to the zone. In dual duct systems, both hot and cold air ducts extend to each zone where mixing boxes blend the air to produce supply air of the proper temperature. In multizone systems, the zone mixing boxes are located at the central air handling unit where hot and cold air is blended to the proper temperature and delivered to the zone in a single duct. There is no thermodynamic or psychrometric difference between the two systems. The type of mixing system employed is generally a function of architectural and economic restraints involved in each specific application.

A schematic of the basic mixing system in the dual duct configuration is shown in Fig. 12. Air is provided by the supply air fan to both the heating and cooling air paths. These air paths are blended at the mixing boxes in response to the zone thermostat as shown. Fig. 13 exhibits the relationships between zone thermostat output, zone mixing damper position, cold duct temperature and hot duct temperature. In this case, the set point of the thermostat is 74^{o}F and the throttling range is 4^{o}F. Over this throttling range, thermostat output varies from 3 PSI to 13 PSI. The hot air damper position varies from 100 percent open at zone temperatures up to 72^{o}F to 100 percent closed at zone temperatures of 76^{o}F and over. The cold air damper position varies from 100 percent closed at zone temperatures up to 72^{o}F to 100 percent open at zone temperatures of 76^{o}F and over. The temperatures of the dual air paths are fixed and maintained by their respective discharge thermostats. The zone mixing damper positions illustrate the blending action of the mixing boxes when the zone thermostat is between 72^{o}F and 76^{o}F. Note that when zone temperature is within the throttling range, hot and cold air is always blended to obtain the supply air. This is the fundamental cause of inefficiency with mixing systems.

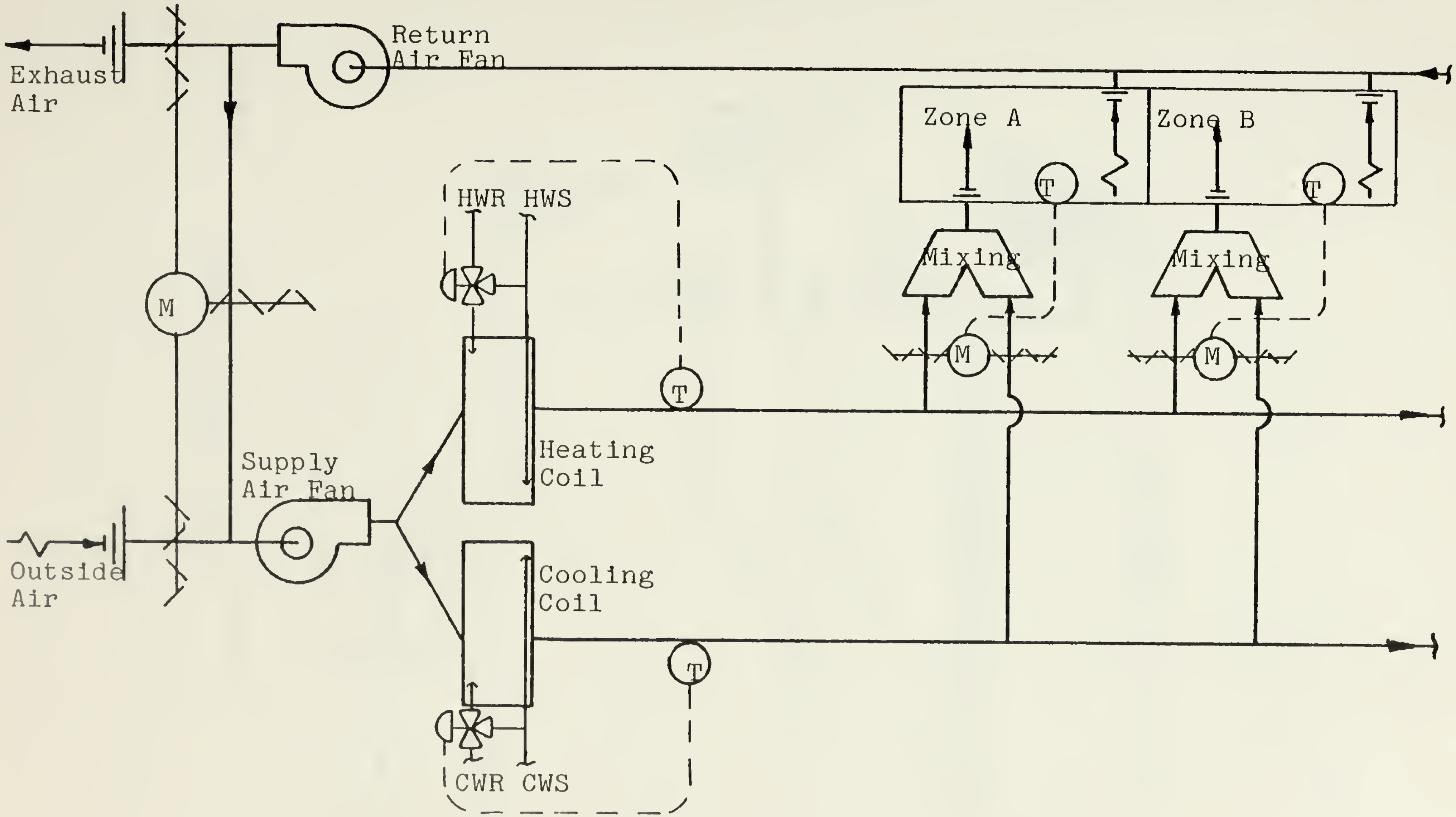

FIGURE 12. BASIC CONSTANT VOLUME MIXING SYSTEM SCHEMATIC

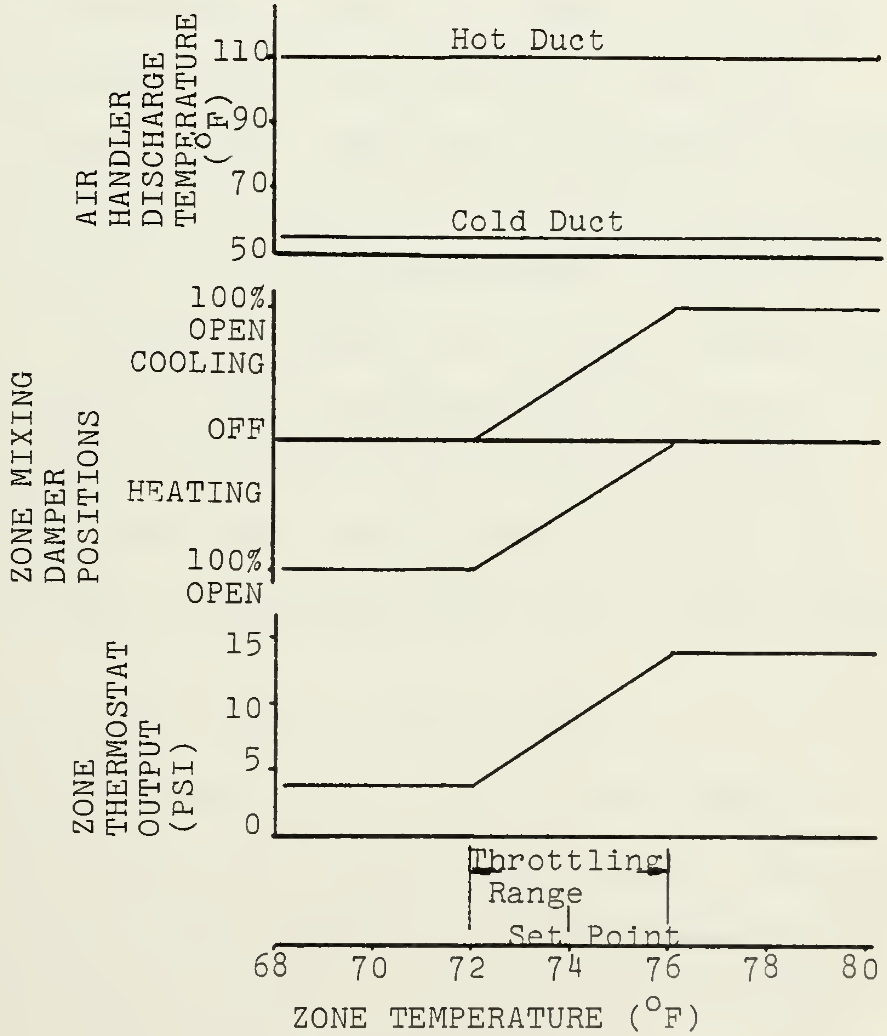

FIGURE 13. BASIC CONSTANT VOLUME MIXING SYSTEM CONTROL LOGIC

Low Cost Control Adjustments

Energy saving adjustments discussed for single zone systems are equally useful for mixing systems. Unoccupied manual shutdown and minimal outside air intake will save a considerable amount of energy. An energy conservation program on a building with a dual duct system in Columbus, Ohio, reported a total metered saving of forty-four percent of the annual heating and cooling energy as a result of unoccupied shutdown of the HVAC equipment.[30] Manually raising the cold duct temperature and lowering the hot duct temperature will minimize the energy losses associated with mixing the air streams. Control of the worst case heating zone and worst case cooling zone must not be sacrificed in this reset process.

Quick Fix Control Modifications

Automatic reset of the chilled water supply temperature (Section 3.4) and hot water supply temperature (Section 2.3) will save energy in a mixing system as in the systems discussed above. Automatic HVAC equipment shutdown by time clock during unoccupied periods will also save energy. Dead band controls and air handler discharge temperature reset schemes are applicable to mixing systems and will be discussed further. Schematics of the control additions and control logic necessary to implement these

air handler discharge temperature reset schemes are applicable to mixing systems and will be discussed further. Schematics of the control additions and control logic necessary to implement these modifications are shown in Figs. 14 and 15.

A comparison of the modified control logic (Fig. 15) with the basic control logic (Fig. 13) reveals that the zone thermostats now act to control the hot and cold duct thermostat setpoints in addition to zone damper positions. The zone mixing dampers still blend hot and cold air in response to the zone thermostat in the temperature range from 72°F to 76°F as in the basic system. The big difference with the modified control system is that the temperature of the air being blended is nearer 78°F and 70°F than 105°F and 55°F. This blending of air streams still wastes energy, but a much smaller amount due to the smaller temperature differences.

It is important to note that the cold duct thermostat is reset by the high signal from the selector as shown in Fig. 14. Similarly, the hot duct thermostat is reset by the low signal from the selector. This insures that no zone is allowed to get too warm or too cool. Fig. 15 depicts the best possible hot and cold duct temperatures. This situation would occur when all zone temperatures were between 72°F and 76°F. Predicted energy savings for discharge air temperature reset and

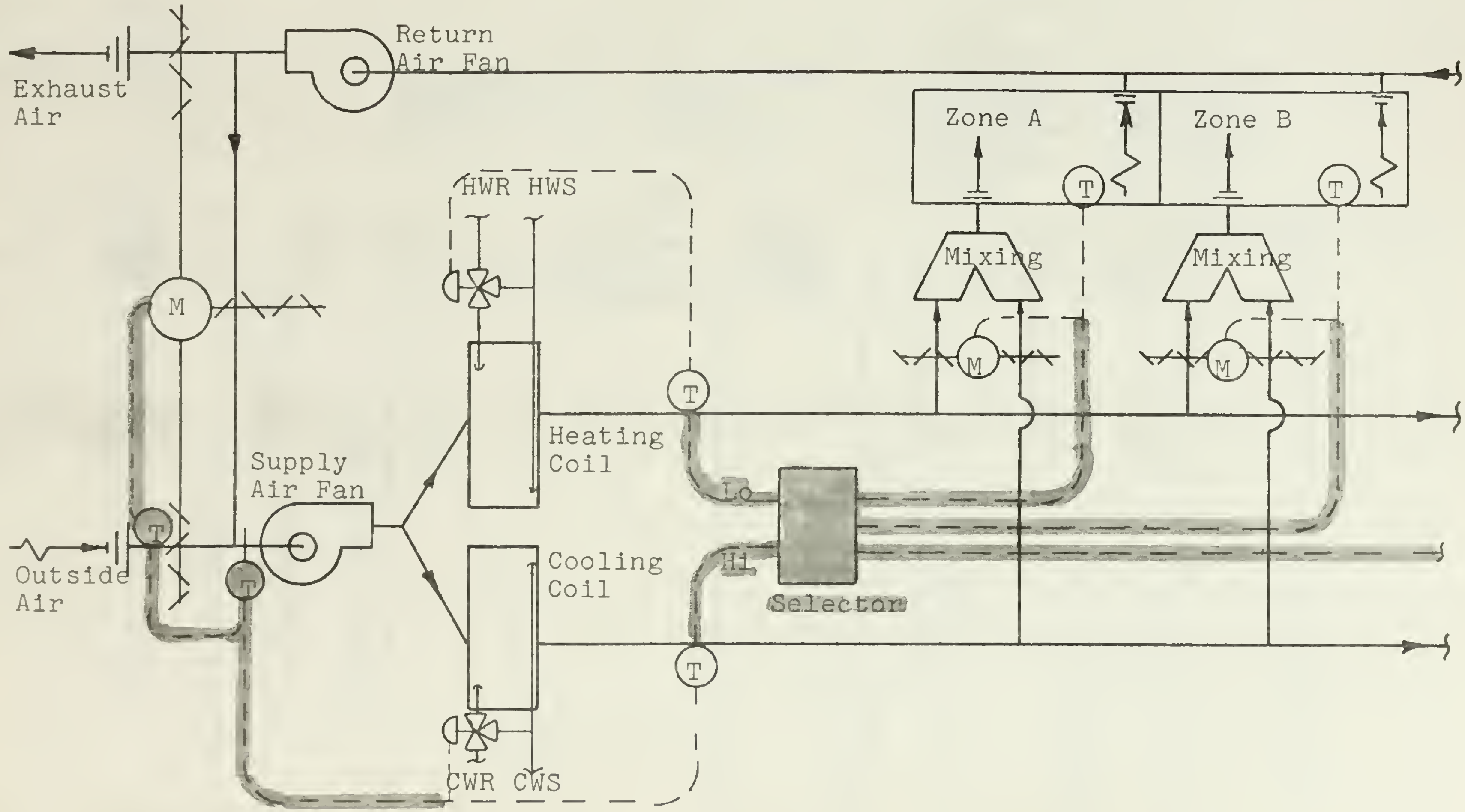

FIGURE 14. MODIFIED CONSTANT VOLUME MIXING SYSTEM SCHEMATIC

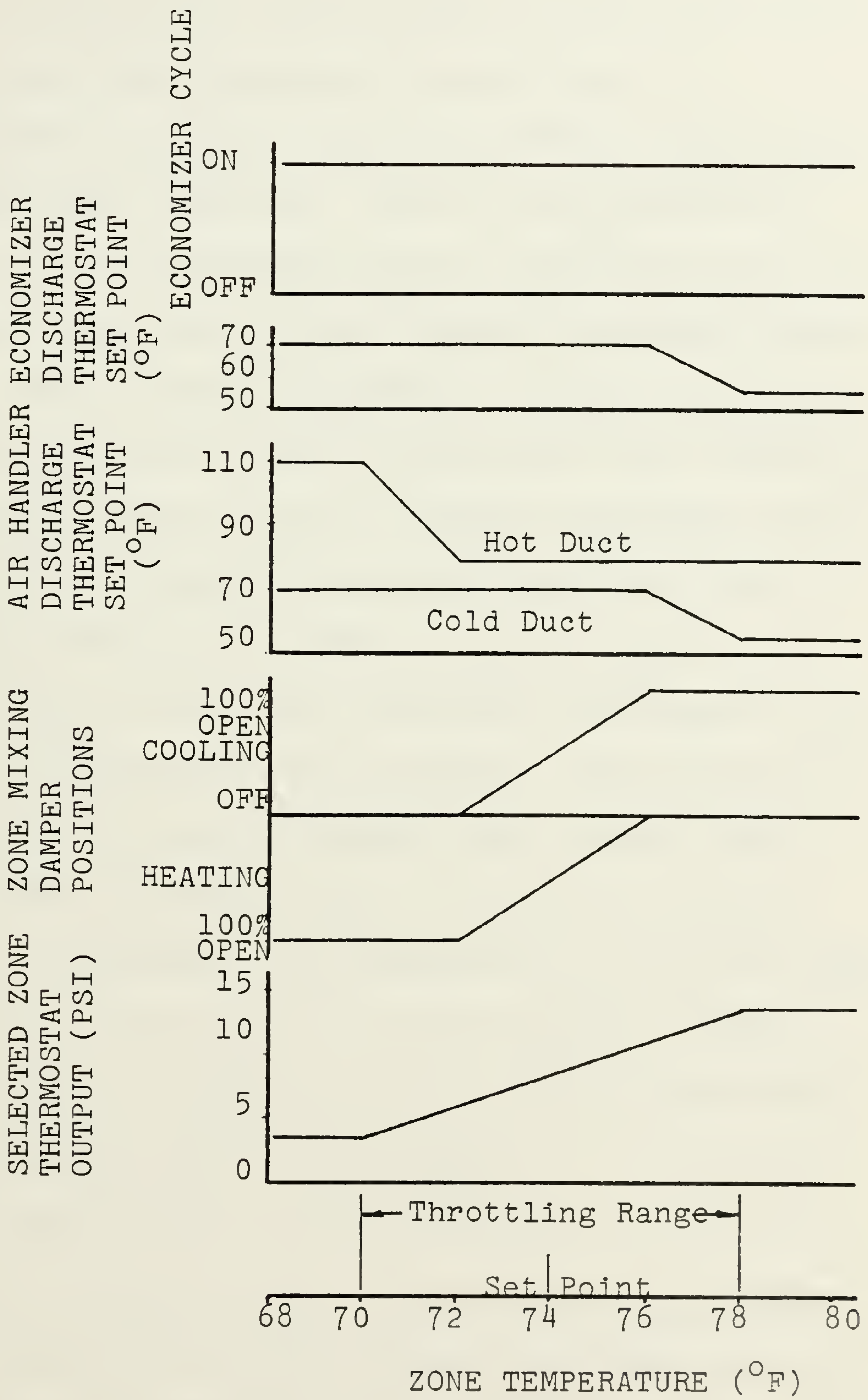

FIGURE 15. MODIFIED CONSTANT VOLUME MIXING SYSTEM CONTROL LOGIC

dead band controls will be discussed in the next section in conjunction with economizer applications.

Another potential quick fix control modification has recently been reported. Work at the University of Illinois on air temperature control loops[35] in dual duct applications indicates the air handler discharge thermostats can affect energy consumption. (This is not zone thermostats but the hot and chilled water coil thermostats.) The throttling range of the air handler discharge thermostats should be as small as possible consistent with control loop stability in order to save energy. The reason for this is that coil efficiency increases as the control loop feedback error decreases. Small throttling ranges result in smaller feedback error values. The Illinois report estimates that in a dual duct system, reducing both discharge air thermostats' throttling range from 10.8°F to 3.6°F could save approximately twenty percent of the instantaneous heating and cooling energy. Annual performance was not discussed.

Minor Control System Retrofit

An economizer cycle, similar to the system described in Section 2.4 of this report will save energy in a mixing system. Control and operation would be the same as described for the single zone system. The reset schedule of the economizer discharge thermostat would be

identical to the cold duct discharge thermostat reset schedule. Enthalpy override should be provided.

Savings as a result of dead band controls, discharge air reset and economizer cycles applied to mixing systems are predicted by several authors. Schoenberger calculated an annual heating energy savings of twelve percent from economizer discharge temperature reset.[28] Simulations of buildings in Pensacola, Florida, Great Lakes, Illinois, and San Diego, California, predict annual energy savings of approximately forty percent for these three modifications.[22]

Installation of an intelligent time clock as discussed for a single zone system in Section 2.4 of this report is equally applicable to a reheat system. Similar savings would result.

Major Control System Conversion

A prime candidate for major conversion is altering the system to variable air volume operation. Analysis of converting a large office building in Los Angeles to variable air volume predicted a thirty-three percent annual energy savings.[24] Variable air volume mixing systems will be covered in Chapter VII.

An interesting system conversion reported by Claremont College involves separating the outside and return air paths, and using hot and cold supply air fans.

Return air is directed to the hot air path and outside air to the cold air path by air guides or turning vanes. Metered heating energy savings in the forty to fifty percent range were recorded as a result of this split system addition. Control complexity is increased in this system as a result of flow measuring requirements necessary to keep the building static pressure within bounds.

CHAPTER V

ALL-AIR VARIABLE VOLUME COOLING ONLY SYSTEM

The Basic System

The cooling only variable air volume (VAV) system was developed to handle multiple zone cooling loads from a single central air handler. The central air handler discharge air temperature is fixed and air is distributed to all zones as shown in figure 16. Each individual zone is supplied through a terminal that varies supply air volume in response to the zone thermostat. Figure 17 depicts a possible relationship between zone temperature, zone supply air volume, air handler discharge thermostat set point, and economizer control loop. Zone supply air volume need not be reduced to zero as shown. Rather a minimum volume of supply air could be provided at low zone temperatures by proper setting of the VAV terminal dampers. The economizer control loop is always on in this arrangement since this is a cooling only central system. Energy savings at part load conditions result from reducing the volume of air supplied to the zone. A direct result of reduced volume is reduced annual fan energy consumption. If heating is required, it is accomplished by an independ-

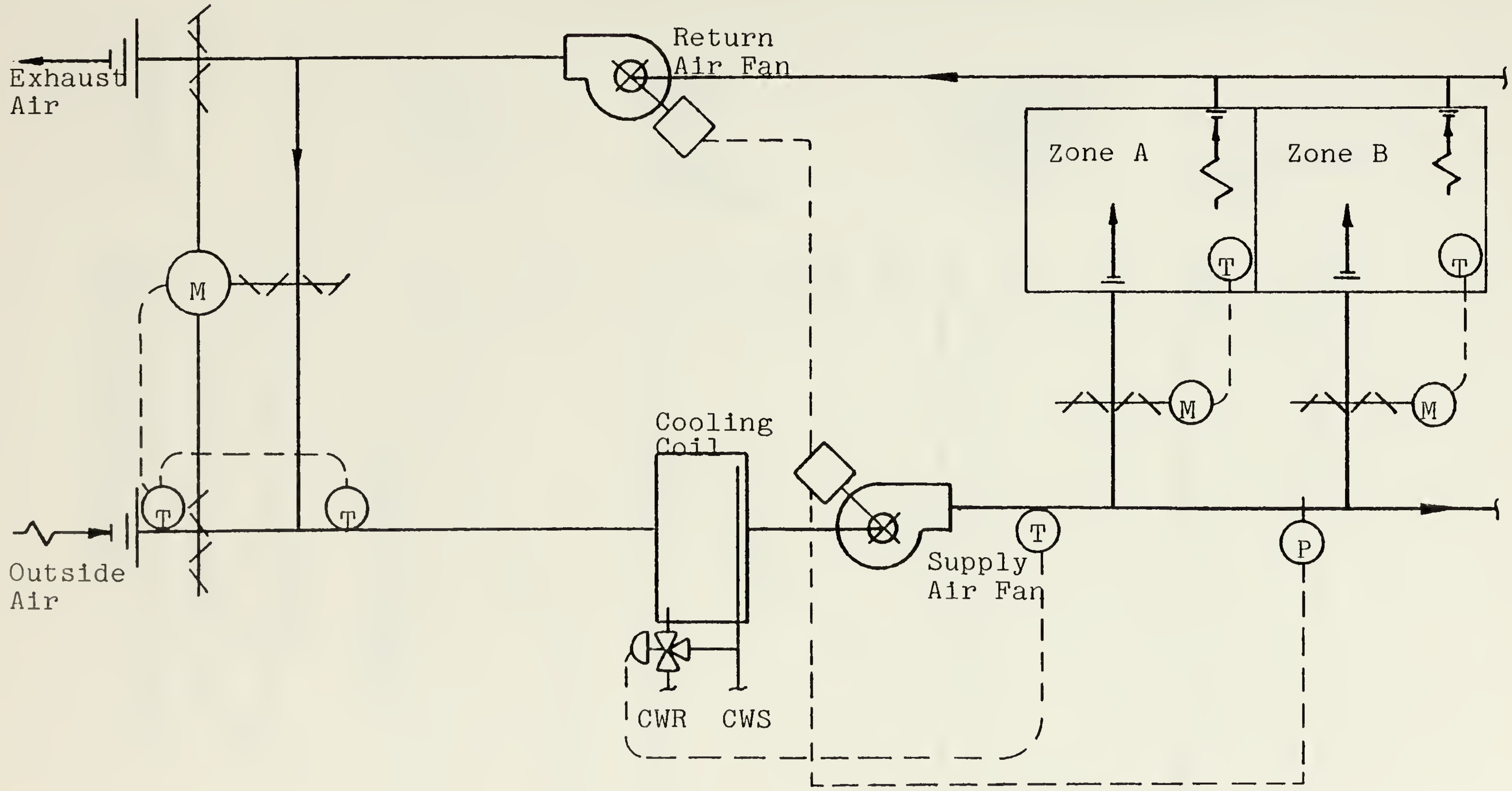

FIGURE 16. BASIC VARIABLE VOLUME COOLING ONLY SCHEMATIC

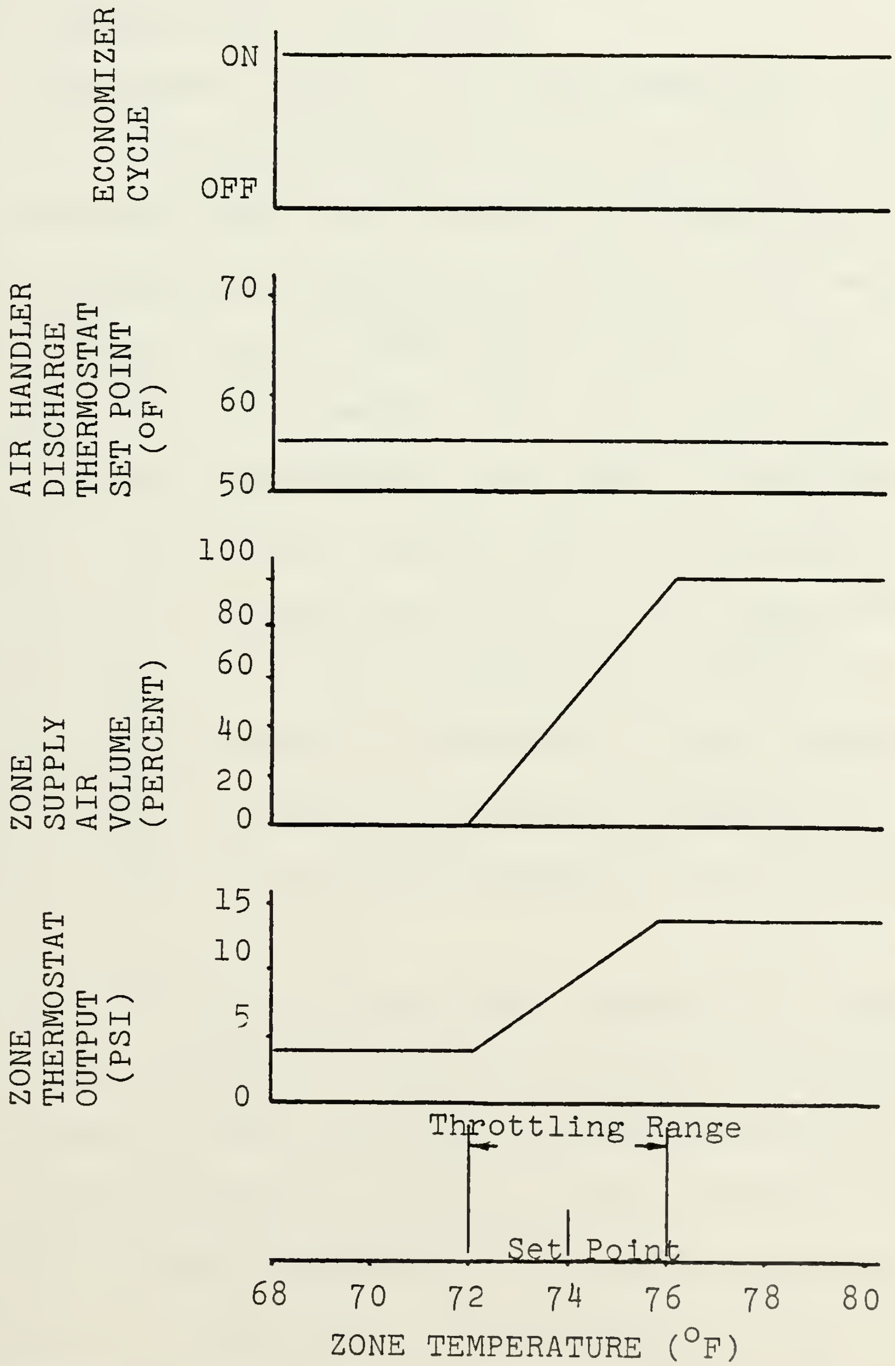

FIGURE 17. BASIC VARIABLE VOLUME COOLING ONLY CONTROL LOGIC

ent system located at the perimeter of the building. Fin tube radiation is a common perimeter system that is used with cooling only VAV systems.

Four common methods of accomplishing fan volume control are: discharge dampers, fan inlet vanes, variable speed motors or blade pitch control on in-line fans. Relative fan power consumption for each of these methods of volume control for one fan type is shown in Fig. 18.[11] Inlet vane control is commonly used and represents an acceptable compromise between first cost and operating efficiency. Solid-state variable speed motors generally offer life cycle savings and in some cases could produce simple paybacks of two years or less when compared to inlet vane installations.[5] The method of fan volume reduction is best determined based on the specific characteristics of the air handling equipment involved and fan type.

Control of the central fan volume is critical in this type of system. The zone terminal units modulate at the behest of their individual thermostats without regard to the cumulative results of their actions at the central fan. Static pressure in the main supply duct is a function of the operation of the terminal units. High static pressure, the result of minimum air volume rates, increases the required fan horsepower and introduces un-

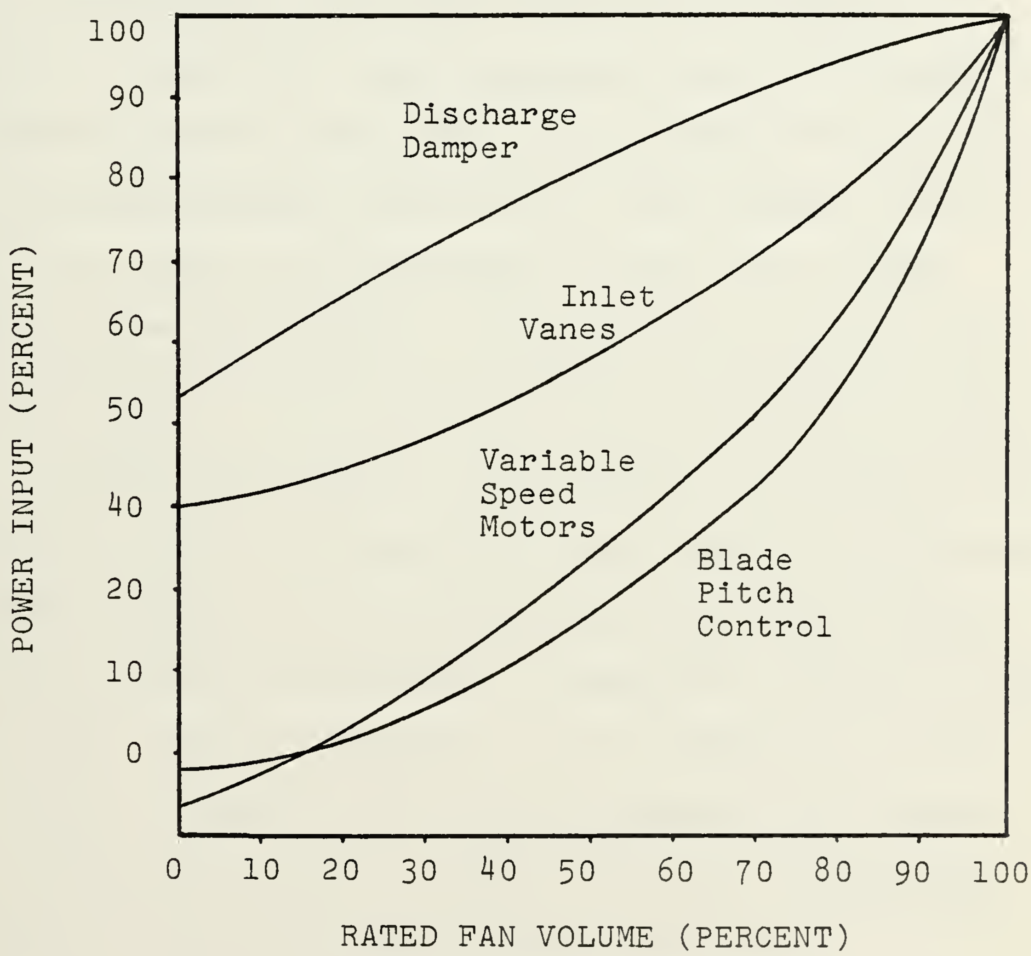

FIGURE 18. FAN POWER CONSUMPTION

desirable flow through the terminal units. Static duct pressure then, is a good candidate for the controlled variable. A pressurestat is used to operate the central fan volume controller. The location and set point of the pressurestat is very system specific. Minimum pressure must be maintained at the most remote zone terminal at all times. Therefore, the pressurestat must be located in the system in such a way that the transients from the fan or local zone terminal boxes do not cause erratic control action, yet still be close enough to the fan to sense overall system performance. Location of the pressurestat is often made in the field using trial and error procedures.

Another advantage of the variable air volume system comes about from the diversity of zone terminal operations. Very few systems will ever operate with all zones demanding full volume simultaneously. Therefore, the size of the central air handling equipment can be reduced by a diversity factor. Reduced initial size combined with volume control that requires the minimum fan power consumption results in an efficient air moving installation.

Variable air volume presents some problems not normally encountered with constant volume systems. Attention must be given to air distribution patterns and diffuser performance at low air volumes. Minimum outside air for ventilation must be provided for all operating conditions. This may require complex interlocking of fans

and damper motors. Fan selection becomes more critical. Fan operating characteristics must be checked at both minimum and maximum flow. In addition, control methods to maintain balance between the supply, return and other fans may be required. These problems are solvable, with the resulting HVAC system approaching real energy efficiency. Although a variable air volume system is one of the most efficient that can be used a review of energy saving measures is included.

Low Cost Control Adjustments

Manual shutdown of the system when the building is unoccupied will save energy in existing VAV systems. Heating requirements while the building is unoccupied will be handled by the independent perimeter system. Minimum outside air settings will also save energy in a VAV system. The set point of the zone thermostat is also a good source of energy savings. Manual adjustment of the thermostat set point to the upper end of the comfort zone for cooling loads and lower end of the comfort zone for heating loads is just common sense.

Quick Fix Control Modifications

As in the single zone constant volume system, several simple control modifications can be made to save energy. Automatic thermostat setback, dead band controllers, hot water supply temperature reset and chilled

water supply temperature reset are all excellent sources of energy savings with a cooling only variable air volume system.

A primary area to effect savings is in control of the perimeter heating system. This system must be sequenced with the cooling such that simultaneous operation of the two systems does not occur. Fig. 19 demonstrates control logic that might be employed to obtain the desired action. As is shown, a wide throttling range is used. Perimeter heating is controlled by thermostat outputs in the 3 to 6 PSI range. Zone supply air dampers are controlled by thermostat outputs in the 8 to 13 PSI range. This results in a 2 PSI dead band where both perimeter heating and cool air supply are shut off. This minimizes energy wasted due to operation of independent heating and cooling systems in the same space.

Minor Control System Retrofit

Economizer cycles and intelligent time clocks as described in Section 2.4 of this report are equally applicable to single zone variable air volume systems. Energy reductions would be similar when applied to both systems.

Major Control System Conversion

All-air variable volume cooling only systems are intrinsically one of the most efficient HVAC systems

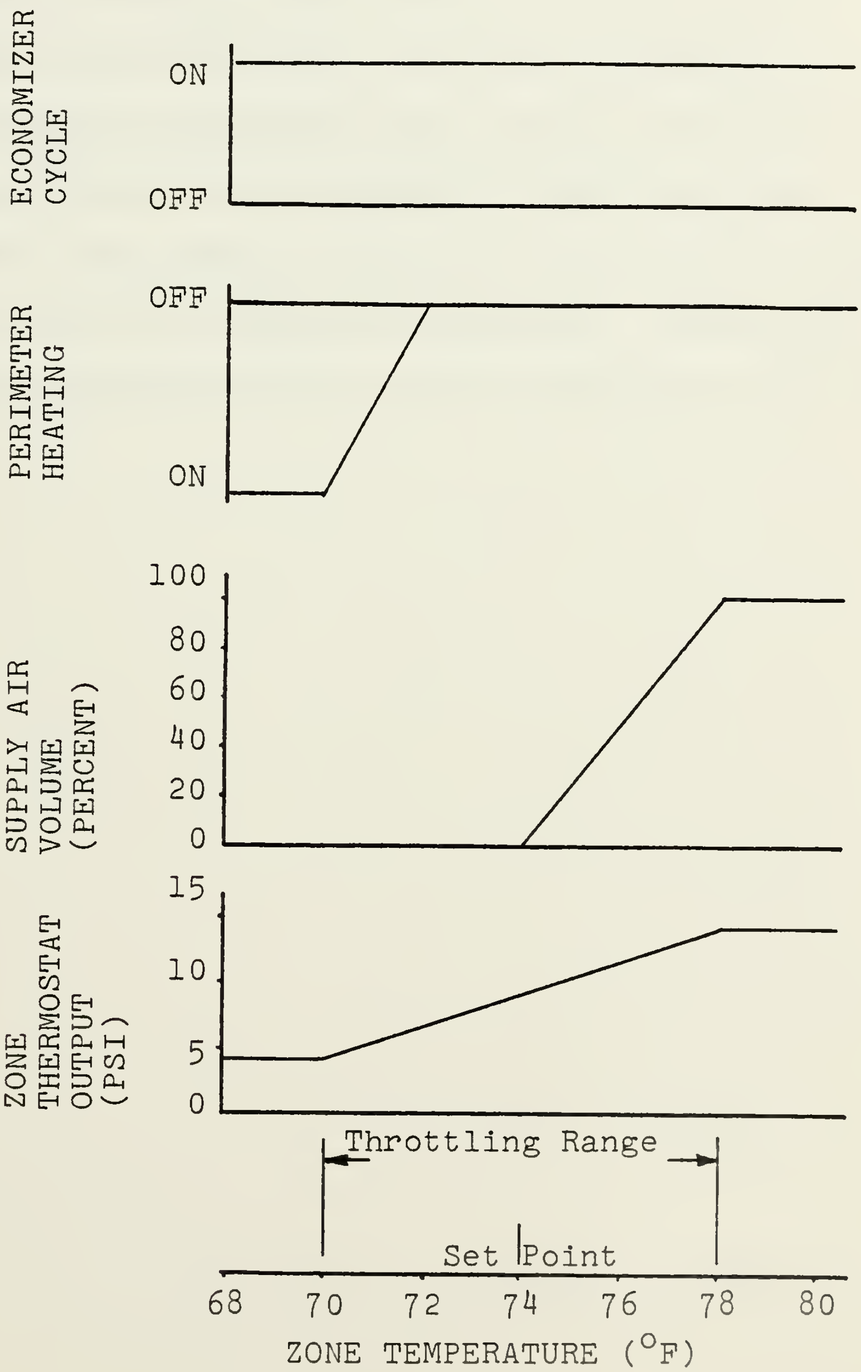

FIGURE 19. VARIABLE VOLUME COOLING ONLY WITH PERIMETER HEATING CONTROL LOGIC

available. When coupled with a reasonable perimeter heating system, VAV systems generally will consume the least amount of energy of any system in common use.[36] This is only a generalization, as local climate and specific building requirements may produce situations where VAV systems would not perform as well as other systems. For this reason, few if any major control system conversions would be economically feasible. Therefore, major control conversions will not be considered for this system.

CHAPTER VI

ALL-AIR VARIABLE VOLUME TERMINAL REHEAT

The Basic System

The VAV reheat system, shown schematically in Fig. 20 is similar to the constant volume system shown in Fig. 10. The primary difference being the addition of central fan volume controls and zone variable volume terminals. This system permits excellent control of buildings containing many zones of varying loads. Heating and cooling zones may be serviced simultaneously from a single duct supply system. As with the constant volume reheat system energy is wasted in heat required zones as cool air from the central air handler is reheated.

Terminals for volume control of each individual zone are operated by the zone thermostat. Fig. 21 depicts a possible arrangement of reheat valve and damper positions relative to zone thermostat output. As shown, the reheat coil valve is operated at 3 to 6 PSI thermostat output. The zone terminal damper operates from full open to a predetermined minimum position at thermostat outputs from 13 to 10 PSI. In the dead band from 6 to 10 PSI

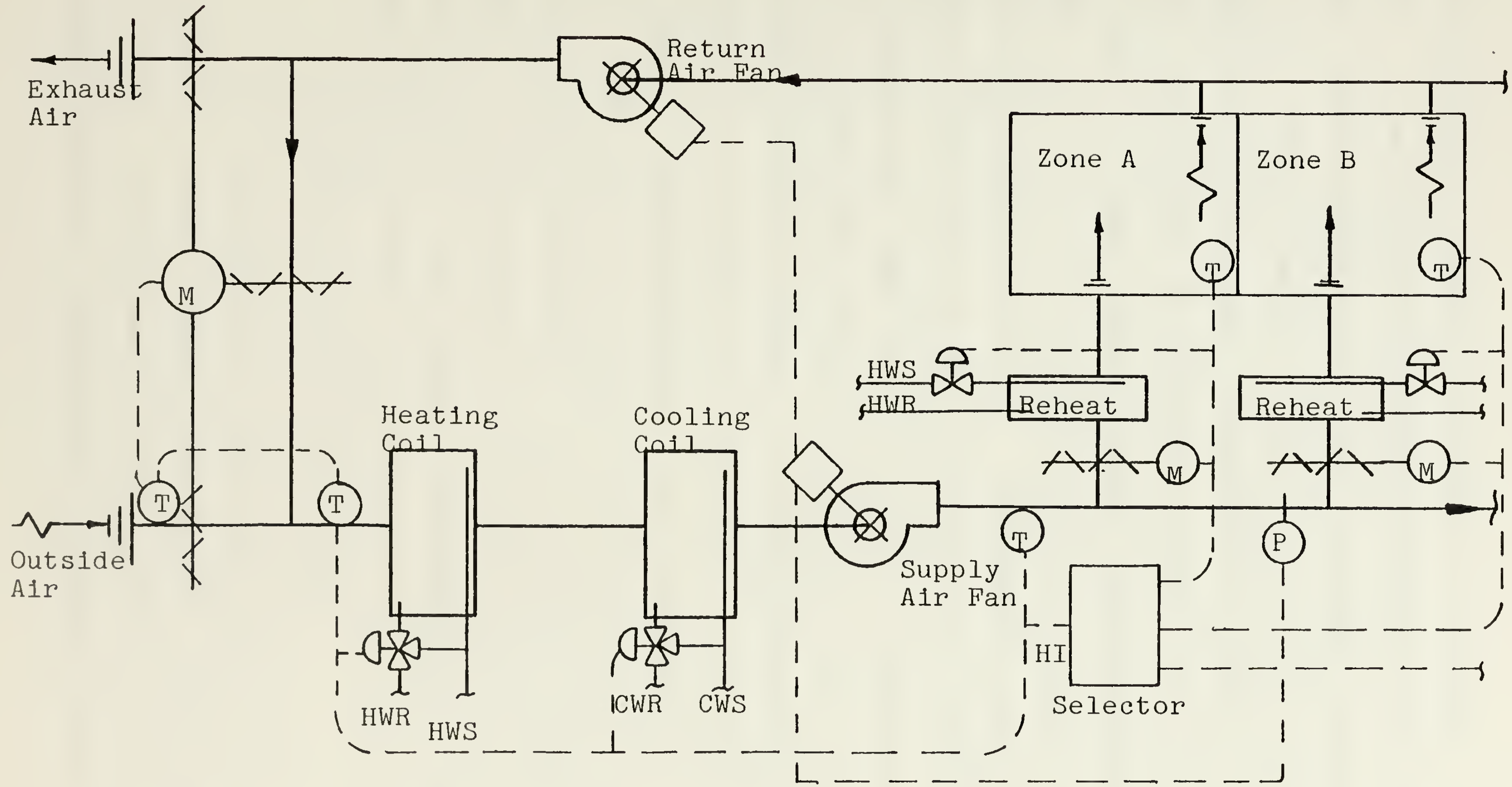

FIGURE 20. VARIABLE VOLUME REHEAT SCHEMATIC

only minimum air volume is supplied to the space. Also, shown is the economizer discharge thermostat set point reset schedule and the air handler discharge thermostat set point reset schedule. These two set point reset schedules are coincident. Thermostat set point reset from 70°F to 55°F occurs at thermostat outputs of 10 to 13 PSI. The result of these reset schedules, valve positions and supply air volumes on the zone terminal discharge temperature is also shown in Fig. 21. Minimum fan energy and thermal energy input at the air handler is required in the zone temperature range from 72 to 76°F. Reheat energy is not permitted until the zone temperature drops below 72°F. The most economical sequence of varying zone supply air volume and zone supply air temperature is dependent upon the specific characteristics of each installation.

Control of the central fan volume is critical in this type of system as it was in the VAV cooling only system. The same kinds of central fan controls will be used in the VAV reheat system. Opportunities to save energy with VAV reheat are discussed in the next sections.

Low Cost Control Adjustments

The adjustments for this system would be the same as for the constant volume reheat system. Manual shutdown of the HVAC equipment when the building is unoccupied; minimum outside air settings; and adjusting the zone

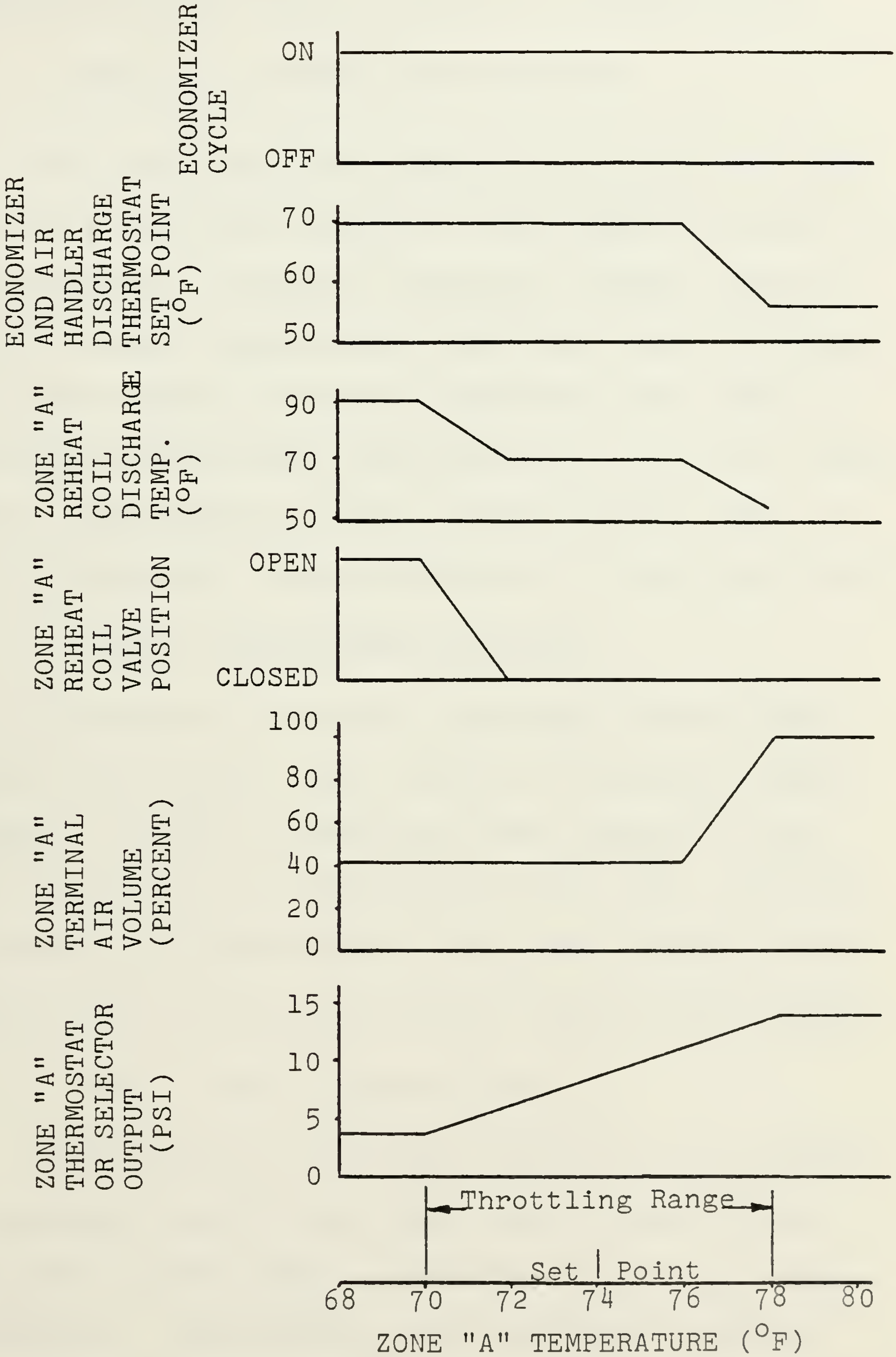

FIGURE 21. VARIABLE VOLUME REHEAT CONTROL LOGIC

thermostat set point are all excellent energy savers.

Quick Fix Control Modifications

The following modifications are effective energy savers in a VAV reheat system as discussed in Section 3.3 of this report. Automatic thermostat setback; reset of hot water supply temperature; dead band controls; reset of the air handler discharge temperature; and reset of the economizer discharge temperature are all valid energy savers. The schematic in Fig. 20 and control logic in Fig. 21 demonstrate the interactions of these modifications.

Minor Control System Retrofit

Economizer cycles and intelligent time clocks fall into this realm. Test results of measured energy savings as a result of applying these measures to VAV reheat systems are not available at this time. However, it follows that these measures will save energy in this system as they did in the constant volume reheat system.

Major Control System Conversion

Elimination of the reheat aspects of this system is the primary major change that can be looked at for a VAV reheat system that has undergone all of the above improvements. Specifically, the building's perimeter zones can be provided with an additional heating system that is sequenced with the central air system such that

they didn't operate simultaneously. In this manner, the reheat coils can be eliminated. The resulting VAV system would operate in a cooling only mode, with heating loads handled by the perimeter system when required.

CHAPTER VII

ALL-AIR VARIABLE VOLUME MIXING SYSTEM

The Basic System

This system is identical to the constant volume mixing system shown in Fig. 14 with the addition of central fan volume control. Central fan volume control would be accomplished as described in the preceding chapter for VAV reheat systems. The central equipment discharge temperatures would be controlled and reset in the same manner as shown in Fig. 15. Varying the air volume supplied by the mixing box is a simple matter of changing the sequencing of the zone damper positions.

Fig. 15 shows a schedule of operation of a typical set of zone dampers in the constant volume mixing system. The hot air damper modulates from 100% open at 72^{o}F to closed at 76^{o}F. The cool air damper modulates from closed at 72^{o}F to 100% open at 76^{o}F. Consider now, Fig. 22 which depicts the control logic for a zone in the VAV mixing system. The schedule of operation of the zone mixing dampers is nearly the same. In this case, however, the hot air damper modulates from 100% open at 71^{o}F to

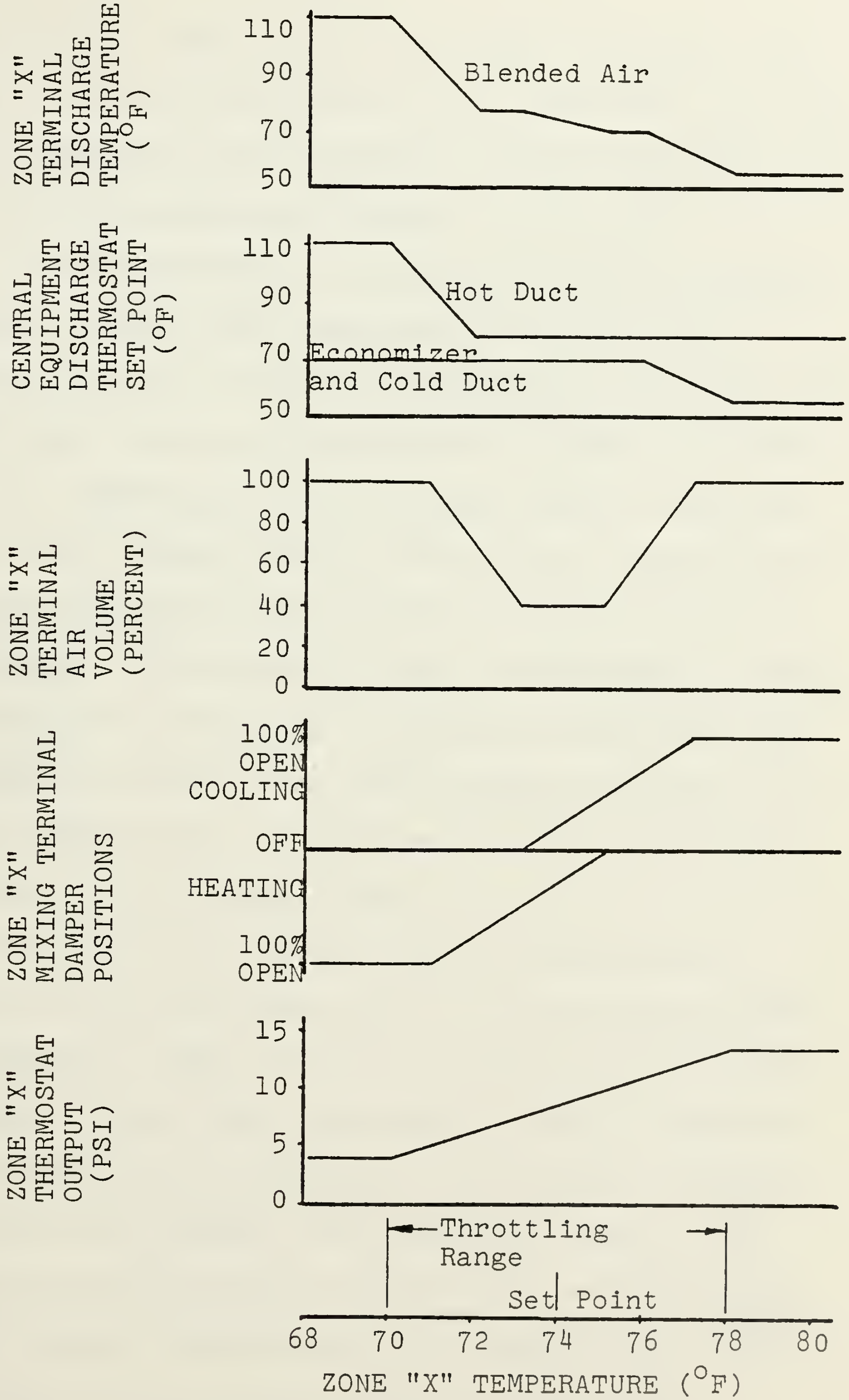

FIGURE 22. VARIABLE VOLUME MIXING CONTROL LOGIC

closed at 75°F. And the cool air damper modulates from closed at 73°F to 100% open at 77°F. The effect of this sequence change on the zone mixing terminal discharge air volume and air temperature is shown in Fig. 22.

The temperature of the mixing terminal discharge air tracks the hot duct temperature and cold duct temperature except in the zone temperature range from 73°F to 75°F where the two air streams are blended. In this range, the temperature of the mixing terminal discharge air will fall between the hot and cold duct temperatures. Of course, mixing hot and cold air to obtain tepid air wastes energy. The amount of waste is minimized, however, by narrowing the temperature difference between the two air streams as shown in the reset schemes in Figs. 14 and 15. Energy waste can also be minimized by lowering the volume of air actually mixed.

Fig. 22 shows the air volume delivered as a function of the zone temperature. Air delivered in the zone temperature range of 73°F to 75°F is shown at 40% of maximum volume. This percentage is easily adjusted by sequencing the zone dampers in the terminal to open and close at any desired zone thermostat output. For example, a zone that is not continuously occupied might have the terminal dampers set up to provide zero flow at, or a range around, the zone thermostat set point.

Conversely, an area with a continuous known load such as lighting in an interior zone can be set up such that the minimum calculated volume of air necessary to handle the cooling load is always provided.

The most economical sequence of varying zone supply air volume and zone supply air temperature is dependent upon the specific characteristics of each installation.

Low Cost Control Adjustments

Unoccupied manual shutdown; minimal outside air; and manually raising cold duct or lowering hot duct temperatures will result in significant energy savings in any system not already incorporating more sophisticated controls.

Quick Fix Control Modifications

Automatic reset of chilled water supply temperature; automatic reset of hot water supply temperature; HVAC equipment shutdown or set back by time clock; air handler discharge thermostat set point reset; and dead band controls are control modifications applicable to this system. Refer to Chapter IV for more complete descriptions of these control modifications.

Minor Control System Retrofit

An economizer cycle with enthalpy override and automatic reset of the discharge temperature should be looked at as a potential retrofit project for the VAV mixing system. Also, an intelligent time clock would produce energy savings similar to those discussed in Section 2.4 of this report.

Major Control System Conversion

Separation of the outside and return air paths by air flow vanes is a possible energy saver for the right system. This conversion was discussed in Chapter IV for a constant volume mixing system.

Complete elimination of blending air for zone supply is necessary to eliminate energy waste in this system. One solution to this problem is to eliminate the hot air path entirely, substituting a perimeter heating system instead. The perimeter heating system would be sequenced in such a manner that the cool air and heat would not be provided simultaneously. The resulting VAV system would operate in a cooling only mode, with heating loads handled by the perimeter system when required.

CHAPTER VIII

EQUIPMENT FOR IMPLEMENTING NEW CONTROL STRATEGIES

The control system hardware necessary to conserve energy in existing buildings is available from most HVAC system manufacturers. Thermostats, humidistats, pressurestats, transmitters, controllers, motors, and time clocks necessary to accomplish the modifications discussed in the preceding chapters have been available for many years. These devices result in basic local control of HVAC functions. More sophisticated controls such as microprocessor based intelligent time clocks and central monitoring systems enhance energy savings over basic localized control to some extent.

The primary advantages of microprocessor based central control systems derive from the ability to accomplish much of the monitoring and required control actions from a central point rather than actual savings in energy over an optimized local control system. These systems offer tremendous advantages to the maintenance staff by allowing more efficient use of personnel and providing complete and accurate data on which to base

operational decisions. Energy monitoring and control systems offer several services in addition to control of the HVAC system. Primary among these are demand limiting, data collection and storage, utilities metering, security monitoring, life-safety systems and preventive maintenance notifications. The combined services offered by central monitoring and control systems are extremely attractive and have resulted in their increasing use in new facility construction.

The tendency to install the best and most recent state-of-the-art HVAC control system must be reviewed in light of what the system can really accomplish and what needs to be done. If on and off control will do the job, install a time clock not a central system. Keep the controls as simple as possible and still accomplish the required control action. Economy, effectiveness, and reliability will follow.

CHAPTER IX

CONCLUSIONS

Well designed control systems offer many opportunities to save energy in existing buildings. Since buildings are unique in design, use, construction and location, generalizations are difficult and exceptions will appear for every rule. The fundamentals of good control strategy have been well stated by Spethmann[33] in his four principles of control for energy conservation:

1. Run equipment only when needed;
2. Sequence heating and cooling, don't supply both at the same time;
3. Provide only the heating and cooling actually needed;
4. Provide heating and cooling from the most efficient source.

Application of these principles will result in efficient control systems for most HVAC systems.

Constant volume all-air HVAC systems have been thoroughly covered in the literature. The most effective control strategies for these systems are well established. Much less has been written on variable air volume all-air

systems. Of particular interest would be studies of the most efficient sequencing of supply air volume and supply air temperature in VAV reheat and VAV mixing systems. Since both of these properties can be varied to respond to changing load conditions, it follows that there must be a most efficient combination of temperature and volume for any given system and load. If the most efficient combination for a class of VAV systems could be predicted, then control strategies could be developed to optimize typical VAV installations.

Key considerations in control modification programs are comfort levels and control complexity. Considerable savings in annual energy consumption can be realized by improving the control of HVAC systems. This energy savings should not be obtained by sacrificing the occupants comfort, or by making the system so complex that it is difficult to install and maintain and thus becomes unreliable. This is a difficult area, since both comfort and control complexity are somewhat subjective. General guidelines in this area are to keep the throttling range of the room thermostat within the comfort zone established by ASHRAE in their comfort standard[2] and to keep the control system as simple as possible and still accomplish the required control action.

The advantages of control modifications to save energy include minimum disruption of an occupied facility during installation of the new controls and minimum costs of implementation. The low cost adjustments and quick fix modifications discussed in this report offer significant energy savings for little investment of money. Control modification compares favorably with architectural or other modifications to existing structures to save energy.

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